“ANALYTICAL SIMULATION, FABRICATION AND DESIGN OF COMPRESSED AIR DRIVEN ENGINE FROM FOUR STROKE PETROL ENGINE”

A THESIS

SUBMITTED IN PARTIAL FULFILLMENT OF THE REQUIREMENTS FOR THE AWARD OF THE DEGREE OF

MASTER OF TECHNOLOGY

IN

THERMAL ENGINEERING

Submitted by:

AMIT

(2K16/THE/17)

Under the supervision of

DR. RAJESH KUMAR

PROFESSOR

DEPARTMENT OF MECHANICAL ENGINEERING

DELHI TECHNOLOGICAL UNIVERSITY

(Formerly Delhi College of Engineering)

Bawana Road, Delhi-110042

JULY, 2018

DELHI TECHNOLOGICAL UNIVERSITY

(Formerly Delhi College of Engineering)

Bawana Road, Delhi-110042

CANDIDATE'S DECLARATION

I, AMIT, Roll No. 2K16/THE/17 student of M.Tech (Thermal Engineering), hereby declare that the project Dissertation titled "ANALYTICAL SIMULATION, FABRICATION AND DESIGN OF COMPRESSED AIR DRIVEN ENGINE USING FOUR STROKE PETROL ENGINE" which is submitted by me to the Department of Mechanical Engineering, Delhi Technological University, Delhi in partial fulfillment of the requirement for the award of the degree of Master of Technology, is original and not copied from any source without proper citation. This work has not previously formed the basis for the award of any Degree, Diploma Associate ship, Fellowship or other similar title or recognition.

Place: Delhi **(AMIT)**

Date:

DEPARTMENT OF MECHANICAL ENGINEERING

DELHI TECHNOLOGICAL UNIVERSITY

(Formerly Delhi College of Engineering)

Bawana Road, Delhi-110042

CERTIFICATE

I hereby certify that the project Dissertation titled "ANALYTICAL SIMULATION, FABRICATION AND DESIGN OF COMPRESSED AIR DRIVEN ENGINE USING FOUR STROKE PETROL ENGINE" which is submitted by AMIT, Roll No. 2K16/THE/17, Department of Mechanical Engineering, Delhi Technological University, Delhi in partial fulfillment of the requirement for the award of degree of Master of Technology, is a record of the project work carried out by the student under my supervision. To the best of my knowledge this work has not been submitted in part or full for any Degree or Diploma to this University or elsewhere.

Place: Delhi

Date:

(DR. RAJESH KUMAR)

PROFESSOR

DEPARTMENT OF MECHANICAL ENGINEERING

ACKNOWLEDGEMENT

It is said that gratitude is a virtue. This part is dedicated to special thanks that I would like to deliver to the people who helped me in making the fulfillment of this thesis project possible.

I take great pride in expressing my unfeigned appreciation and gratitude to my learned mentor **PROF. RAJESH KUMAR**, and Department of Mechanical Engineering, Delhi Technological University (Formerly Delhi College of Engineering), for their invaluable inspiration, guidance and continuous encouragement throughout this project work. His critics and suggestions on my work have always guided me towards perfection. This work is simply the reflection of his thoughts, ideas, concepts and above all his efforts. Working under his guidance has been a privilege and an excellent learning experience that I will cherish for a long time.

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AMIT

2K16/THE/17

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LIST OF SYMBOLS

η = Efficiency

R = Universal Gas Constant

P = Pressure

T = Temperature

C_P = Constant Heat at Specific Pressure

R_p = Pressure Ratio

ρ = Density

v = Velocity

H = Head

n = Length of Connecting rod to Crank Radius

D = Bore dia.

t = Thickness of Ring

n’ = Number of Ring

p = Pressure over Rings

μ = Coefficient of Friction

F = Force exerted over Piston

θ = Crank Angle

T = Torque exerted over Crank

ω = Angular Velocity of Crank Shaft

ABSTRACT

As the modern world is pressed hard with the fuel and energy crises, compounded by all kinds of pollution, any technologies which bring out relief to this problem will be considered as a healing on the wound. One of such technologies, is basically the development of somewhat new engine which runs on compressed air and doesn't require any of well known fuels like petrol, diesel, CNG, Bio-diesel, LPG, hydrogen etc.

This technology replaces most types of fuels known today and also solves the pollution related issues to a large extent as the exhaust is non- polluting and at a lower temperature than atmosphere when measured practically up to 5ºC. Since the engine runs on high pressurized air, exhaust undoubtedly being only air, making it very close to zero pollution engine. Heat generation is not there because no combustion is present there, hence the engine doesn't require any cooling system due to which cost is reduced. Also the weight, volume and vibration are reduced.

An Compressed Air Driven Engine uses the Compressed Air Technology(CAT) for its working. CAT now a days is widely preferred in different industries for research and development in developing different types of drives for various purposes. CAT is not very much complex. It is based on principle that if we compress the air in a cylinder then the air will be holding some energy within it due to compression. Now this energy will be used in the desired purpose. When the compressed air inside the cylinder expands, the energy is being utilized to do the desired work.

Early cost analysis have indicated that the engine is very much cost effective when compared with the petrol and diesel engines and the operational cost is approximately ten times lower. Though the value of efficiencies are lower as the losses were high. However this concept could be applied in a professionally designed engine or in already existing engines to improve the performance.

CHAPTER 1

INTRODUCTION

At the first glance idea of running the engine on compressed air seems very much exotic to be real. In fact, if we can do something to make use of compressed air as an aid in running an engine it will be a fantastic idea. As we all of us know, air is present all around us, it never runs sort, it is a green source of energy and also available free of cost. An Compressed Air Driven Engine (CAE) makes use of Compressed Air Technology (CAT) for its operation. Now a days CAT is widely used and preferred by different industries for carrying out research and for developing different types of drives used in various purposes. CAT is not so complex but quite simple. It is based on principle that if we compress the normal air in a cylinder, the compressed air will hold some extra energy (which comes due to the compression work) within it. Now this energy can be utilized for some useful purposes. Now when this compressed air expands in the cylinder, the energy stored is released to do the useful work.

So this energy in the form of compressed air can be utilized to move or displace a piston from its position. This is the basic concept behind working of an Air Driven Engine. The engine uses the energy from expansion of the compressed air in the cylinder to drive the piston of the engine. So an Compressed Air Driven Engine can be basically considered like a pneumatic actuator which creates the useful work by expanding the compressed air. This work which is extracted from the energy of air is finally utilized to supply the power from the piston to the crankshaft of our pneumatic engine.

In the case of an Compressed Air Driven Engine, there is no fuel burning and hence no combustion takes place inside the engine. Hence it is a non-polluting and a less dangerous engine. The material it requires is of light weight only since it need not have to withstand the elevated temperatures. Since there is no combustion which is taking place, hence there is no need of mixing fuel with air. Here the compressed air works as a fuel and is directly fed into our piston cylinder arrangement. The air simply expands inside the cylinder and provides useful work on to the piston. This work which comes over to the piston provides enough power to the crankshaft for its rotation.

1.1 COMPRESSED AIR TECHNOLOGY

Air can be compressed into very small volumes due to its less density and can be stored at high pressure in suitable containers. Such air when compressed and stored in a container is associated with some amount of energy. When this stored compressed air is being released freely(in the surrounding) it then expands and hence releases the energy associated (or stored) with it. This released energy can be further utilized to provide the useful work. Compression, storage and the release of air together is called as the Compressed Air Technology. This technology is utilized in different pneumatic systems now a days. There is a lot of research going on in this field to improve its applications.

Compressed air is now regarded as fourth utility now, after electricity, natural gas (like CNG, LPG etc.), and water. Compressed air has found its use in or for:

- Pneumatics, where the pressurized gases are used to do work.
- Vehicular transportation by using a compressed air in the vehicle propulsion.
- scuba diving
- To inflate the buoyancy devices.

- Cooling by using vortex tube.
- Gas dusters in cleaning of electronic components where water can not be used.
- Air brake (in rail) systems
- Air brake (in road vehicular) systems
- Starting of the diesel engines (an alternate to the electric starting)
- Compressed air breathers (like Suisse Air)
- Pneumatic guns .
- Pneumatic screw drivers

1.1.1 TWO STROKE ENGINE

A conventional two-stroke engine is one that completes its thermodynamic cycle in single rotation of the crankshaft compared to twice rotations in case of a four-stroke engine. This increases the efficiency theoretically by accomplishing the beginning of the suction and compression in one stroke and combining expansion and exhaust in another stroke. In this way the two-stroke cycle often provides relatively high specific power.

Gasoline spark ignition (S.I.) version is particularly more useful in the lightweight applications such as in chainsaws and this concept is also being used in the diesel compression ignition (C.I.) engines in large and also in some less weight sensitive applications like in ships and locomotives. All the functions are solely controlled by the covering and uncovering of piston ports as it moves upside and downside in the cylinder. A major fundamental difference which makes it different from a four-stroke engine is that in the gasoline and hot bulb engines, the crank-case is sealed and it forms a part of the induction process. Generally diesel engines have a root blower or a piston pump for scavenging.

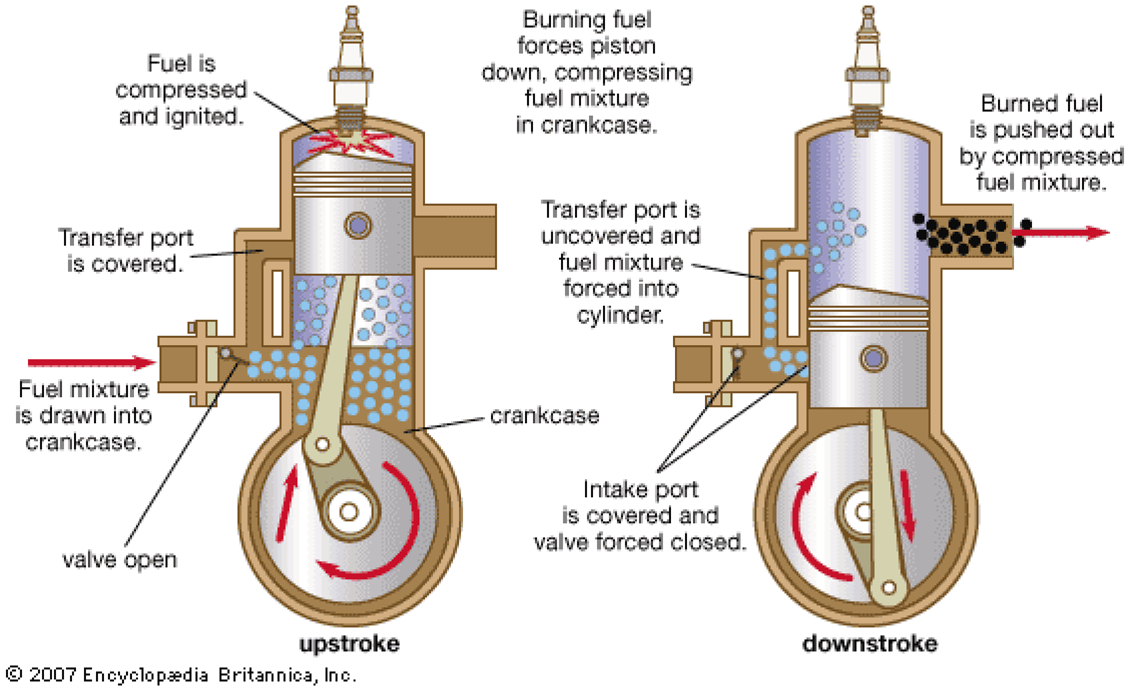


fig.1.1 Working of Two Stroke Engine [4]

Traditional valves are not there in a two-stroke engine. The firing in two-stroke engine takes place once in every revolution. This thing makes the engine efficient and lightweight when compared to the four-stroke systems. The fuel-air mixture in the engine enters through the intake port rather than entering through the valve and the exhaust exits out from an exhaust port. Inspite of using traditional valves the two-stroke engine make use of the piston's position in order to force out the exhaust or suck in the fresh air fuel mixture. Reeds play a very important role in a two-stroke system. Reeds are placed between the carburetor and the intake manifold, opened and closed to allow the air fuel mixture to enter into the case of engine and to trap it, and to ensure that the proper exchange of gasses takes place in the engine. This procedure may sound somewhat complex, but it is, in fact, very effective and easy to understand.

The complete cycle can be explained as :

1) As the piston starts moving from top dead center (TDC) to bottom dead center (BDC) it starts creating a vaccum which draws the air- fuel mixture through carburetor and past reed valve assembly.

2) The piston when moves up from BDC to TDC than the reed closes, which causes the pressure to build up in the cylinder. As the piston movement starts, the intake port gets closed and piston movement starts pressurizing the air-fuel mixture.

3) When the piston reaches to top dead center, then the spark plug ignites for some fraction of time due to which energy is released from the air-fuel mixture leading to downward movement of piston called as expansion

4) After the expansion stroke comes the exhaust stroke. When the piston reaches BDC the exhaust valve starts opening and all the exhaust moves out as piston reaches to TDC from BDC. And then again intake valve opens and the cycle continues

.

1.1.2 AIR COMPRESSOR

Air compressor is a mechanical device that is used to increase the temperature and pressure of the gas by converting electrical power of gas into the kinetic energy by compressing the air, which is then released by the compressor in quick bursts. There are various methods of increasing the pressure, divided broadly into positive-displacement and non-positive displacement types.

In positive-displacement compressors pressure rise is obtained by using the fact that if we decrease the volume of a gas its pressure subsequently increases. Piston-type compressors are using this principle to operate by pumping the air into a chamber by using the piston. These compressors uses uni-directional control valves to guide the air into a chamber, we get the compressed air. Functioning of rotary screw compressors also comes under positive-displacement category. Here we match two helical screws those, when turned, guide the air into the chamber, reducing the volume as screw turn. Vane compressors uses a slotted rotor with different blade placement in order to guide the air into chamber and to compress the volume. Talking about non-positive displacement compressors, they basically include centrifugal compressors. These devices works on the principle that first we provide kinetic energy through the impeller to the fluid i.e, air. After that the fluid motion is retarded due to which the kinetic energy of the fluid gets converted into pressure energy and leading to pressure rise.

General application of compressors includes:

- To supply high pressurized clean air to fill the gas cylinders
- To supply clean air at moderate pressure to a submerged surface diver
- To supply large amount of air at moderate pressure for powering pneumatic tools
- For filling the tires
- To produce large volume of moderately pressurized air for various macroscopic industrial processes (like oxidation in petroleum cooking or in cement plants for bag house purge system).

Most of the air compressors are generally reciprocating piston type, rotary vane or rotary screw type. Centrifugal compressors are generally used in large applications. Generally there are two types of air compressor pumps: Oil lubed (with oil) and oil less. The oil less type of system has comparatively more technical developments, but they are relatively expensive, louder and has less life than the oil lubed pumps. The positive thing is that the air quality is better when compared to lubed pumps. So the best choice will depend on the kind of application user wants.

1.2 THE MDI CAR

After almost twelve years of intense research and development, a French engineer Guy Negre was successful in developing an engine that can become one of the greatest technological advancement of this century. He has designed a very low polluting engine for the urban transport that basically runs on the compressed air. The CATS (Compressed Air Technology System) system for air cars developed by Motor Development International (MDI) is a very significant step for achieving zero emission transportation target, delivering an air vehicle that is very much safe, quiet (less sound producing), has a maximum speed of 110 km/h and also having a range of 200 km. And apart from that the Cost is nothing as compared to run, the Vehicle with Zero Emission range includes- a pick-up truck and a van which was released by the company in 2005.

Guy Negre is head of the R&D department at MDI cars, where the Zero Emission Vehicle (ZEV) prototype are being produced since 1994. Basically the 2 stroke engines are powered by tanks containing compressed air stored at about 150 times the car tyre pressure. The expansion of the air stored in the tanks drives the piston to create the movement, replacing the combustion of the fossil fuels in the conventional petrol and diesel engines. In the air-refilling station (where air is filled in the tanks) it is estimated that it will take between approx three to four minutes in order to re-fuel the tank. At our home, having a 220V plug, it will take around three and a half hours to fill the tank. Air vehicles have significant amount of economic and environmental benefits. With the use of hybrid engines (compressed air + fuel) the air vehicles have their driving range approximately close to 2000 km with almost zero pollution in the cities and with considerable amount of reduced pollution outside the urban areas.

Fig. 1.2 MDI Car Models Working on Compressed Air [12]

Also application of MDI engine (outside automotive sector) opens vast scope of possibilities in other areas also like nautical fields, electric generators groups, co-generation, in auxiliary engines etc. Compressed air energy is a new doable form of energy that allows the easy accumulation and transportation of energy. MDI car company is very much close to initiate the production of engines and vehicles for market sale. The company is being financed from the sale of its manufacturing licenses and various patents all over the globe.

1.2.1 MDI Engine Working

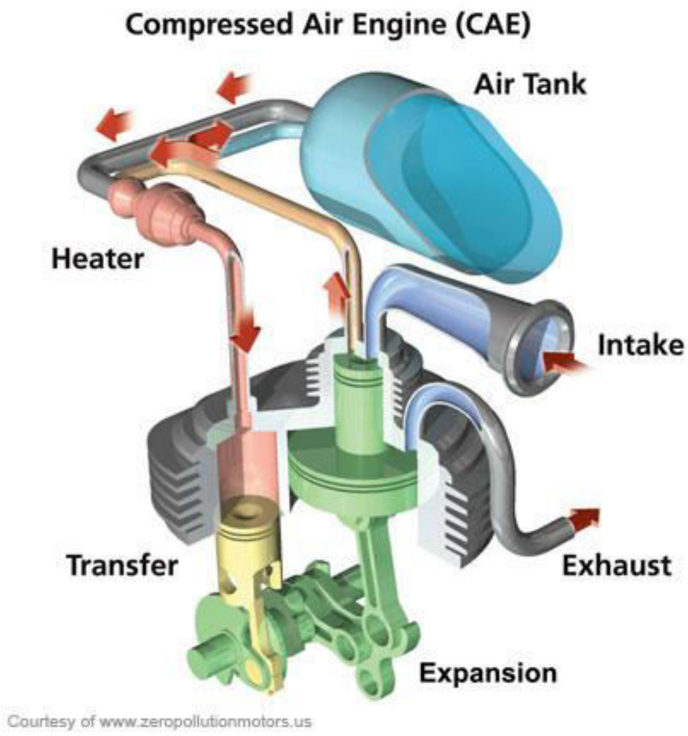


Fig. 1.3 A Typical Demo of MDI Car Engine [32]

Approximately $90m^3$ of air is being stored in compressed form in the fibre tanks of vehicle. The engine is basically powered using the compressed air, air is stored in a tank made of carbon-fibre at 30 MPa (4500 psi). The tank is built using carbon fibres in order to decrease its weight. This engine has also injection similar to that of normal engines, but it uses special type of crankshafts and pistons (when compared to normal engine), which remain at the top dead centre (TDC) for almost 70 degree's of the crankshaft's rotation; this helps in developing more power inside the engine. The expansion of the air inside the engine pushes the piston and creates movement on the crankshaft. The atmospheric air temperature is basically used to re-heat engine and to increase the road coverage. The air conditioning (AC) system uses expelled cold air to cool the cabin . Due to absence of any combustion process and fact that there is no pollution causing elements, the oil change gets required after every 50,000 km.

		Mono-energy	Dual-energy 2	Dual-energy 4
Length	m	2.65	2.65	2.65
Width	m	1.62	1.62	1.62
Height	m	1.66	1.66	1.66
Number of seats	-	3	3	3
Luggage compartment volume	Dm^3	500/700	500/700	500/700
Weight	Kg	550	520	540
Engine	-	41P03	41P01	41P01/4
Power	cv	25	25	50
Max. speed	Km/h	110	125	140
Urban range (zero pollution)	Km	140/150	50	50
CO_2 emission in urban use	g/Km	0	0	0
Non-urban range	Km	80	1650	1500
Non-urban consumption (petrol)	litres	-	1.8	2
CO_2 emission in non-urban use	g/Km	0	35	40
Price (from) taxes included	• 9200			

Table 1.1 MDI Engine Specifications [35]

1.2.2 Additional Features of the MDI Car

Apart from the various features of the MDI car discussed above like its range, emissions, speed, cost etc. There are some other features also which adds to the fur in the cap –

- Light-weight: This vehicular body is made up of fibre glass, which makes this as a light, silent(less noise producing) urban car. The shape of body of the car is tubular, and is basically held together using the aerospace technology. It reaches speed of up to 220 km/h (yet the legal limit is upto 120 km/h).
- It doesn’t have a normal speed gauge. Instead, it contains a computer screen that is used to display the speed.
- The electric system of the car also has a revolutionary design. MDI has made a patent which is bound to reduce importance of the electrical system in cars. The trick lies in using some small radio signals. The system helps in making the car lighter by 20 kilograms and considerably less noise producing.

- When working on single energy mode, car consumes less than a euro (around 0.75 euros) for every 100 km, so it can be said that, that this car consumes 10 times lesser than the gasoline powered cars.
- Its driving range is almost twice when compared with some of highly advanced electric cars in the market (from 200-300 kms or circulation of 8 hours). This is exactly the requirement of the urban market , where approximately 80 % of the cars move less than 60 km/day.
- Car recharging will be done at some gas stations, once market is being developed for this. Filling of the tanks will probably take somewhat 2- 3 minutes at an estimated cost of about 1.5 euro's. Refilling of the car will be required after 200 kms. Car is also connected with a small compressor which can be connected with the electrical network (220V or380V) and can recharge the tank completely within 3 to 4 minutes.
- Since there is no combustion taking place inside the engine, car's oil is needed to be replaced after every 50,000 km.
- Temperature of the air expelled from the engine is in between 0 and -15℃ and thus can be used for the air conditioning purpose inside the car's interior.
- Advanced features like GSM telephone systems, GPS tracking, programmes for the delivery people, Internet connections, emergency systems, voice recognitions, traffic information and map presentation can be incorporated in the car.
- Regarding security, seat belt system is designed differently from what it is known. Basically a part of belt is attached to the floor of car, like the one used in traditional cars. While the other part instead of getting attached towards the other side of car, is also attached to the floor space of the car.

- There is no key used, just an electronic card that will be scanned by the sensors of the vehicle from your pocket itself.

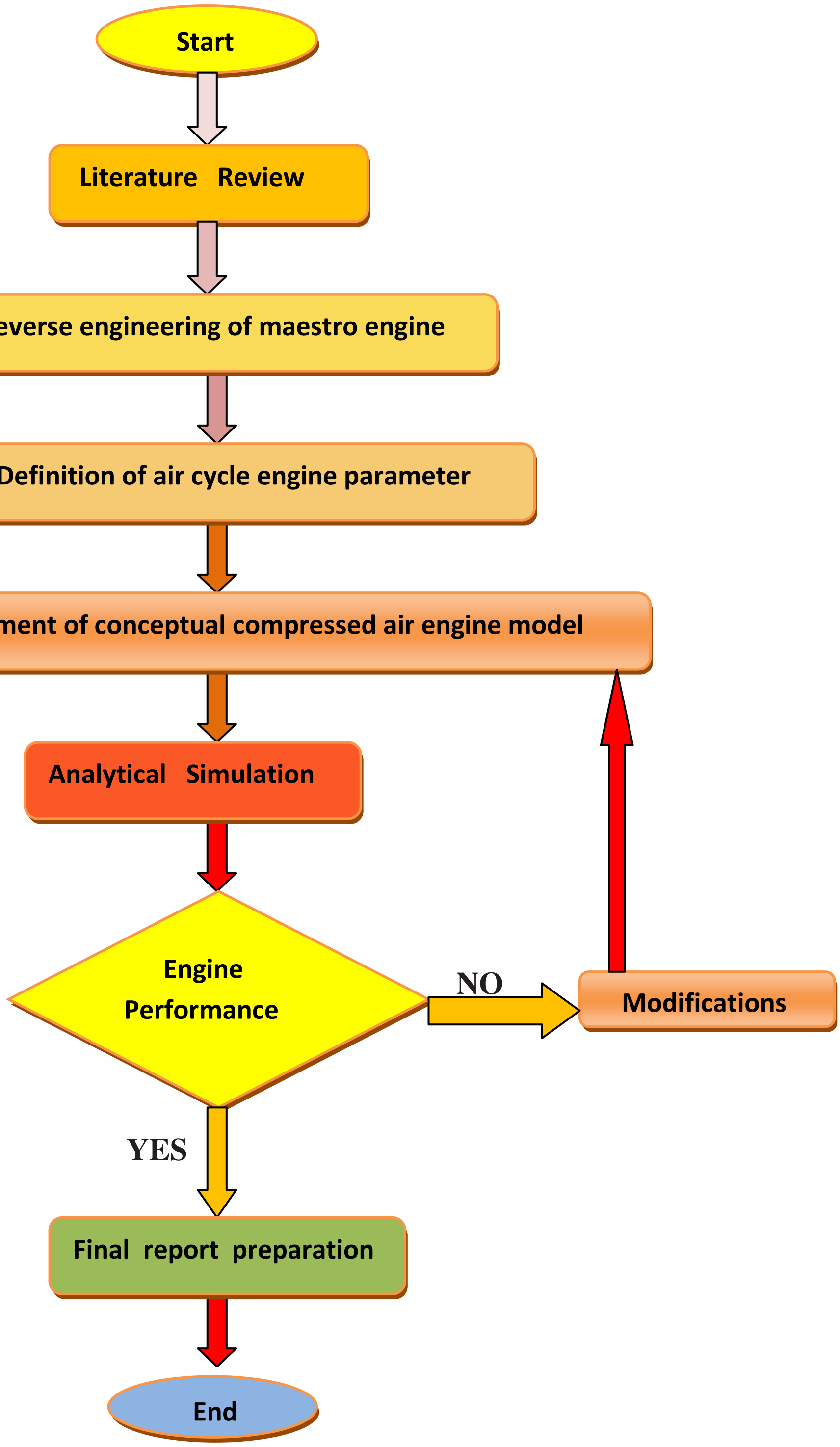
1.2.3 Air car in India

Tata Motors (an Indian company) has signed an agreement to develop an air car with the Motor Development International (MDI) a French company, in order to make it economical for running and to make it pollution free. Although the official date of release of the car is not decided but it will be manufactured for India and reports reveals that it will be very soon.

Fig. 1.4 Proposed Air Car in India by Tata Motors [9]

The car – MiniCAT (Mini Compressed Air Technology) - may cost around somewhere Rs 350,000 in India and will be having a range of somewhere 300kms between refuelling .The cost of single refill will be around Rs 90. In single energy mode the MDI cars consume somewhere Rs 45 for every 100 km. Figure shows proposed car for India which runs on air. The small and innovative (three seats, aesthetic design with small dimensions having boot of a saloon), it poses a great challenge to run such cars on compressed air. The MiniCAT is going to be the city car of the near future.

1.3 FLOW CHART



CHAPTER 2
LITERATURE REVIEW

One can't accurately say that the compressed air as an energy source and its use in locomotives sector is some recent technology. At the start of 20th century (end of the 19th century), the very first approximation to something which might become one day as a Compressed Air Vehicle (CAV) has already existed, when the arrival of first pneumatic locomotive took place. In fact, earlier than this, some two centuries before Dennis Papin proposed this idea of using the compressed air (Royal Society of London, 1687). Later, in 1872 Mekarski's air engine was being used for the street transit system, having a single stage engine only. At that time it was an important advancement in terms of the pneumatic engines, because of its forward thinking making use of thermodynamics, which has ensured that heating of the air (by passing it from various tanks of boiling water) has increased the range of vehicle for fill-ups. Many locomotives manufacturing got started and many regular lines were established (first was in Nantes in 1879). After that in 1892, a new method of heating was introduced by Robert Hardie that helped in further increasing the range for the engine.

However, first locomotive for urban transport was introduced in 1898, by Hoadley and Knight, it was based on the fact that longer the air is kept in an engine more will be the heat absorbed by it and hence greater range. As a result of this a two-stage engine was introduced. Charles B. Hodges will be remembered as the father of compressed air technology when it comes to applying this concepts on the cars. He is the first person, who not only invented the car driven by compressed air but also have considerable commercial successes associated with it. H.K. Porter & Company (of Pittsburgh) sold hundreds of such vehicles to various mining industries in the eastern part of United States because of the safety which this method (of propulsion) which this method had for mining sector. Then, in 1912, American's method was further improved by Europeans, by adding further stage in the expansion of the engine i.e, 3 stages. Some of the research work carried out by different researchers in the field of compressed air driven technology are-

S.No	WORK	YEAR	REFERENCES
1.	In this paper the author analysis are on the basis of working principles and features for these engines, advantages and disadvantages and the point of research in the future and the trend .Through analysis of the compressed-air engine at home and abroad, summarizes the way to increase efficiency and economical efficiency of compressed-air engine.	2008	XY Liu, Y Wang
2.	Author analyzes the thermodynamic efficiency of a compressed-air car powered by a pneumatic engine and consider the merits of compressed air versus chemical storage of potential energy and also the pneumatic–combustion hybrid vehicle technological feasibility and its competence with hybrid electric vehicles.	2009	Felix Creutzig, Andrew Papson, Lee Schipper and Daniel M Kammen
3.	This paper talks about carbon footprints, and fuel costs and exhaust study characterizes the potential performance of CAVs in terms of fuel economy, driving range among their viability as a transportation option as compared with gasoline and electric vehicles including the analysis of energy density and expansion	2010	A Papson, F Creutzig

	losses		
4.	The article presents a dynamic analysis of the compressed air energy storage in the car. The analysis was used to determine those processes most relevant to achieving highest possible efficiency. Simple usage of cars is also performed by taking local conditions from an electricity market.	2011	Łukasz Szabłowskia, Jarosław Milewskia
5.	This paper reviews the state-of-the-art developments of such a technology including the operating principles, function and current status of development .Classification, technical characteristics, key components and system performance of different types of compressed air energy storage systems are also analyzed.	2012	X Zhang, H Chen, J Liu, W Li, C Tan
6.	This paper talks about Impacts of compressed air energy storage plants on electricity market with a large renewable energy portfolio	2013	A. Foley, I. Diaz Lobera
7.	This study presents the applications of piston type compressed air engine on a small size motor vehicle. A conventional 100cc four-stroke IC engine was modified to a two-stroke compressed air engine and the power output has been examined with different intake valve timing and supply air pressures on a test bench.	2013	Wang, Yuan-Wei, Jhih-Jie You, Cheng-Kuo Sung, and Chih-Yung Huang

8.	The present paper gives a brief introduction to the latest developments of a compressed-air vehicle along with an introduction to various problems associated with the technology and their solution	2013	S. S. Verma
9.	This study presents the applications of piston type compressed air engine on a small size motor vehicle. A conventional 100cc four-stroke IC engine was modified to a two-stroke compressed air engine and the power output has been examined with different intake valve timing and supply air pressures on a test bench.	2014	Yuan-Wei Wang, Jhih-Jie You, Cheng-Kuo Sung, Chih-Yung Huang
10.	In this paper effort is made to study various modification and merits & demerits of compressed air engine. This paper talks about the working principle, engine modifications and about actual working of engine	2014	Rohamare,R., B. Tambe Kiran
11.	This paper is reports on the review of compressed air engine for the design and development of single cylinder engine which can be run by the compressed air. Current four strokes single cylinder engine (bikes/moped) can be run on the compressed air with a few modifications that are the main objective of the study.	2014	Kalpesh Chavda, Patel Manish D, Suthar Umang P, Patel Krunal V
12.	Objective of this research paper is to design & modify the four stroke petrol engine into the compressed air engine by modification in the cam lobes and also evaluate the	2014	Nitin Parashar, Syed Mazhar Ali, Sumit Chauhan, Ravi Saini

	comparison of economic characteristics between compressed air engine four stroke SI engines.		
13.	This paper mainly talks about the valve timing diagram of the engine and the various angle modification required in the cam and the gear ratio in order to convert the conventional engine into the compressed air driven engine	2014	Basou Saxena, Ayush Kumar Srivastava, Anu Srivastava
14.	This study investigated a modified intake and exhaust system for piston-type compressed air engines.	2015	Liu, Chi-Min, Jhih-Jie You, Cheng-Kuo Sung, and Chih-Yung Huang
15.	This paper explains the working of the compressed-air vehicle (CAV) which is powered by an air engine using compressed air. Paper also emphasizes on conversion of a 4 stroke single cylinder SI engine into a compressed air engine with the minimum possible modification of the existing design.	2015	Sawan Shetty, Sampath S S, Mohamed Mohtasim Sharafat
16.	This study presents an experimental investigation of an engine driven by compressed air. The compressed air engine is a modified 100 cc internal combustion engine. The engine is modified from a 4-working stroke to a 2- working stroke engine (power and exhaust) by modification of cam-gear system.	2015	Bilal Abdullah Baig, Hakimuddin Hussain

17.	This paper talks about the working principles of compressed air engine using single and double acting pneumatic cylinders and also compares the adiabatic and isothermal work requirements.	2015	Gaurav Kumar Tandan , Gopal Sahu, Prakash Kumar Sen
18.	In this study firstly mathematical models of a single-cylinder engine and a two-stage expansion engine were constructed. Second, the relations between the rotational speed and the output power, torque, efficiency, and cylinder pressure were established using MATLAB simulation software	2016	Liu, Chi-Min, Chin-Lun Huang, Cheng-Kuo Sung, and Chih-Yung Huang.
19.	This paper explains the requirements of such technologies, implementation, comparison with other technologies and possible application areas. First, the layout of such propulsion system is described and associated efficiency terms are presented. Then after, different methods are presented along with detailed implementations and their results are discussed	2017	Marvania, Devang, and Sudhakar Subudhi
20.	This research presents the small-single piston expander for small-scale power generation to use with compressed air storage system. The main contributions of this work is to modify small-single piston engine into the expander and evaluation. The expander was tested to find performance of method including torque, speed, temp. and flow rate is measured.	2017	Tenissara, Nopporn, Sirichai Thepa, and Veerapol Monyakul.

CHAPTER 3
RESEARCH GAPS AND OBJECTIVES

3.1 RESEARCH GAPS IDENTIFIED

Based on the literature review and after studying the research papers on or related to the topic, there are a lot of areas where research can be done like -

- There is no economically viable solution available for a large no. of vehicles which are retiring everyday
- Research is required in the storage of energy in the tanks, since the volume of air is more so it requires large volume tanks which have large weight and are difficult to carry
- Social-economic evaluation of the engine considering engine operations and its performance
- Application of FMS (flexible manufacturing system) to the existing assembly line of vehicle manufacturing.
- Study of hybrid of conventional vehicles with compressed air vehicles.
- Optimization of the speed range of compressed air vehicles in use with the hybrid.
- Software analysis of the compressed air driven engine.

3.2 RESEARCH OBJECTIVES

In this report on Compressed Air Driven Engines our main focus will be on the following key points

- Firstly we will focus on why is there a need of the hour in order to shift from conventional resources to the renewable form of energy. It also includes the use of compressed air as an alternate fuel to drive the automobiles , its necessity and advantages

- Our second objective will be to find the ways by which we can convert a normal SI engine into a compressed air driven engine. What are the various modifications required in the engine in order to achieve it

- Our third and final objective will be to find out the limitations or drawbacks if any of using these engines and check the problems associated in practical implementation of these engines. We will also check the other applications based on this technology

CHAPTER 4
PROJECT METHODOLOGY

The world is changing at a very fast pace. In order to keep with this pace, technological transformation seems to be the only means with the help of which we can ensure places for ourselves in this global market. Concept of "Compressed Air Engine (CAE)" alone cannot guarantee environment friendly and sustained means for modern transportation system. This is due to the fact that in compressed air engines, air is being compressed by using electricity and as we know electricity is developed (in India and the world) mainly by using conventional sources of energy like coal. In the countries like India , china and other parts of the world where there is very immense effect of air pollution on the health of people we can't expect large impact of CAE in day to day life of individuals until and unless some stringent steps or innovation is carried out in this field in order to overcome the adverse effect on the environment.

Another major issue which is concerned with success of Air Powered Vehicle in Indian market is the use of carbon fibre for air storage which results in increase of cost. Till now we are unable to significantly reduce carbon fibre prices, so its use will hinder popularity of such engines among Indian customers. To overcome these issues, we have developed the concept of -

4.1 Turbocharged Injection of Pressurised Air

- Our prime focus of building an air engine is basically to facilitate use of Turbochargers in the intake of air to the engine.

- Use of Turbochargers will provide us with an additional pressure boost of 8 to 9 psi.
- But it's not that if we are limited to this, instead we are using multistage compressors that will assist not only in inc. the pressure of intake air but also in cooling of high pressure air.
- By cooling the high pressure air between the stages, the compression curve will move near to isothermal.
- Work done by the compressor will be less if it's a multi-staged compression for desired pressure ratio. In a multi-stage compressor, there compression takes place in more than one stages with intermediate cooling.
- The air in the first stage is being compressed and after compression it is passed over to the cooler in order to reduce the temperature with a constant pressure.
- This cooled air is then passed to some of the intermediate stages where it again gets compressed and heated. This process continues like this.

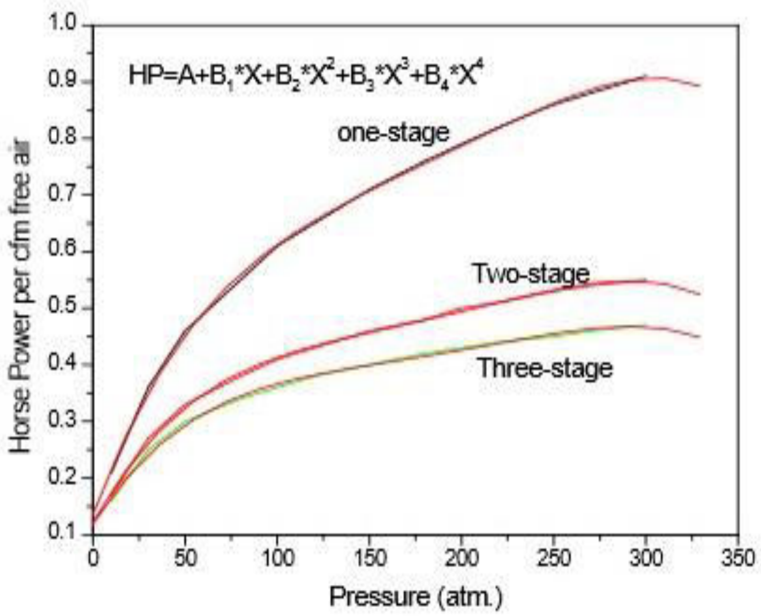


Fig. 4.1 Variation of Power with number of Stages [28]

4.2 Replace fuel tank with air vessel, as engine requires pressurized air as input.

Since the Air Engine requires compressed air for its working. So we don’t need fuel to be stored in the tank, instead we require the fuel tank to be replaced with a compressed air tank.

Fig. 4.2 Compressed Air Tank[3]

4.3 Use of Direction Control Valve For Engine Timing

We basically worked on replacing the cam of the engine which was designed for four stroke operation to assist two stroke cycle, so that inlet at outlet valves are not opened and closed at the same time.

But, early studies and analysis showed that modification of the cam could not provide us the desired objective. Also, we were not able to reach to our final desired calculations (desired working conditions, torque, rpm of engine etc.), in accordance to given engine specifications.

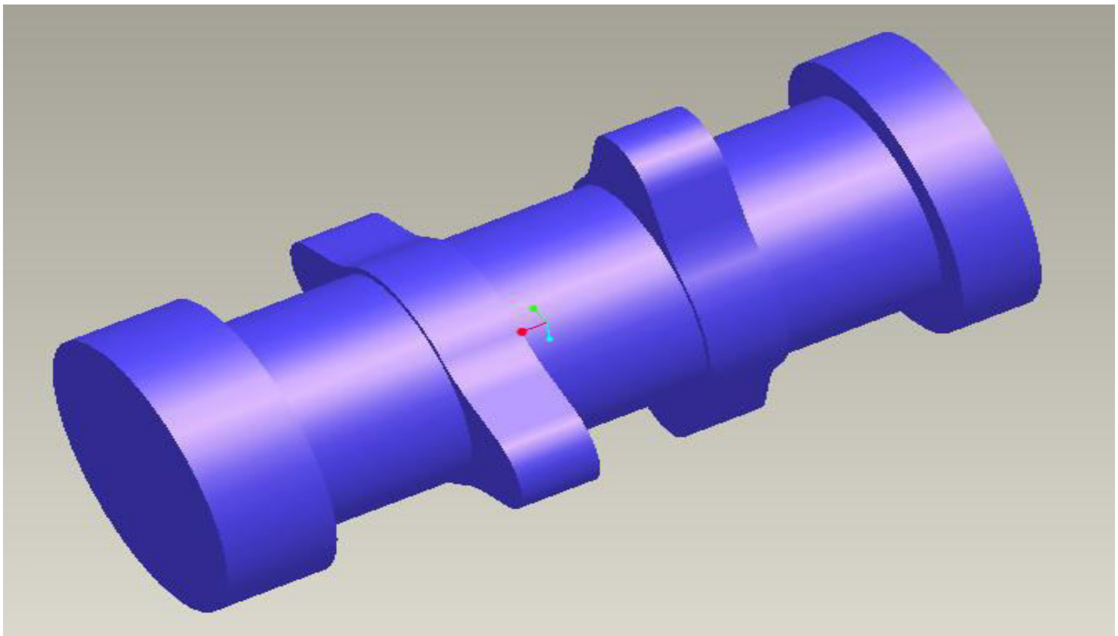


Fig. 4.3 Cam Modifications for Converting 4 Stroke Engine into 2 Stroke

So in order to convert the four stroke cycle into two stroke, we used direction control valve mechanism. Here, a slight offset provided to a bell crank linkage, we can transfer the motion of the flywheel rotation to the reciprocating motion of the pistons inside direction control valve at a desired speed to open and close the single port which is used for both as input as well as output port.

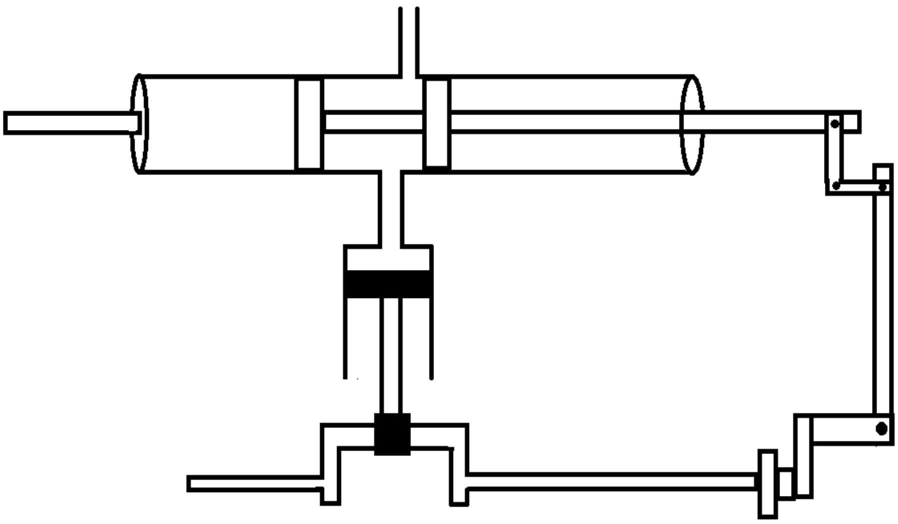


Fig. 4.4 Mechanism For Converting Four Stroke Engine into Two Stroke Engine

CHAPTER 5

ANALYTICAL STUDY OF ENGINE

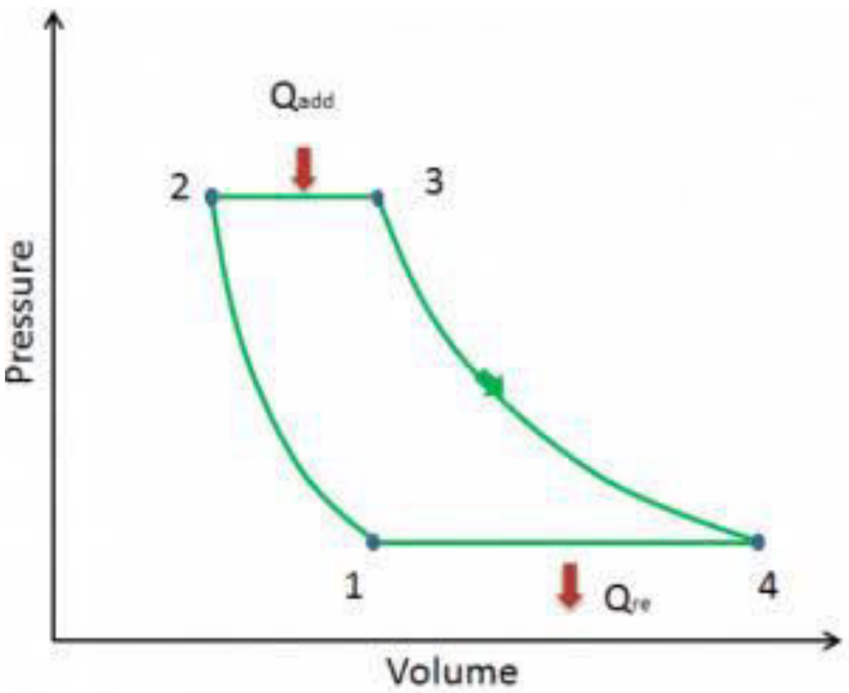


Figure 5.1 Theoretical P-V Cycle For CAE

Process 1-2 : Isothermal compression

Process 2-3 : Expansion at constant pressure

Process 3-4 : Isentropic expansion inside the engine

Process 4-1 : Air discharge at constant pressure from the engine

$\eta = W.D/Q_S = Q_S - Q_R/Q_S$

$\eta = 1 - Q_R/Q_S$

$\eta = 1 - [mR \ln(P_2/P_1) + mC_p(T_3 - T_2)] / [mC_p(T_4 - T_1)]$

$\eta = 1 - [mR \ln(P_2/P_1)] / [mC_p(T_4 - T_1)] - [mC_p(T_3 - T_2)] / [mC_p(T_4 - T_1)]$

Now,

$C_P = \gamma R/\gamma - 1$

So,

$\eta = 1 - [mR \ln(P_2/P_1)] / [m(\gamma R/\gamma - 1)(T_4 - T_1)] - [mC_p T_2 (T_3/ T_2 - 1)] / [mC_p T_1 (T_4/ T_1 - 1)]$

Also,

$T_2/T_1 = (P_2/P_1)^{(\gamma-1/\gamma)} = r_p^{(\gamma-1/\gamma)}$

And,

$T_3/T_4 = r_p^{(\gamma-1/\gamma)}$

So,

$T_2/T_1 = T_3/T_4$

Or,

$T_4/T_1 = T_3/T_2$

Therefore,

$\eta = 1 - [\ln(P_2/P_1)] / [(\gamma/\gamma - 1)(T_4 - T_1)] - [T_2 / T_1]$

$\eta = 1 - T_1 [\ln(r_p)] / [(\gamma/\gamma - 1)(T_3 - T_1] - [r_p^{(\gamma-1/\gamma)}]$

As far as working of compressed air concept is concerned, we would be using air as a working medium from a compressor in which the inlet to the direction control valve will be 100 psi (6.9 bar)

Pressure input to the direction control valve = 100 psi (698793.10 N/m^2)

Velocity of input air can be carried out by: P = $\frac{1}{2}\rho V^2$

Taking ρ = 1.2 kg/m^3 (for the given compressed air temperature)

Thus velocity of input air = 1080 m/sec.

From the continuity equation, $a1 * v1 = a2 * v2$,

We get: Velocity of air in the direction control valve = 275.51 m/sec.

Head loss in the direction control valve due to sudden expansion is given by:

$$H\ (lost) = \frac{(v1^2 - v2^2)^2}{2*g}$$

Thus considering the pipe losses in the system, final air pressure over the piston would be, P = 314456.89 N/m^2.

Now, for the Bajaj DTSi engine that we have,

Stroke length = 0.0544 m

Crank radius ($\frac{stroke\ length}{2}$) = 0.0272

Length of connecting rod = 10.88 cm

Bore diameter (Piston head diameter) = 5.4 cm

n = $\frac{length\ of\ connecting\ rod}{crank\ radius}$ = 4

Area of the piston head over which compressed air is injected = 2.3× 10^{-3} m^2.

Force exerted over piston by gas pressure = Pressure over piston × Area of piston head

= 723.25 N

Force due to friction between piston rings and cylinder = $\pi \times D \times t \times n' \times p \times \mu$= 4.75 N

Where, D = Bore diameter

t = thickness of ring = 3.5 mm

n' = number of rings = 2

p = pressure over rings = 0.04 N/mm^2

μ = Coefficient of friction = 0.1

Here, we are neglecting the effect of inertia force due to reciprocating mass of the engine because the reciprocating parts are accelerated from rest, during the first half of the stroke and retarded, during the latter half of stroke. The inertia force due to the acceleration of the reciprocating parts, opposes the force on the piston due to difference of pressure in the cylinders on the two sides of the piston. On the other hand, the inertia force due to retardation of the reciprocating parts helps the force on the piston.

Inertia force of reciprocating mass is given by:

$$m \times w^2 \times r \times (\cos\theta \ + \frac{\cos 2\theta}{n})$$

As can be seen from the equation, we have varied values for inertia which depends upon crank angle (θ).So, we neglect the inertia force as it adds as well as subtracts the force and thus can be eliminated in general design considerations.

Thus final force exerted over piston, F = 718.5 N

Crank effort or turning moment or torque on the crankshaft can be calculated by:

$$T = \mathrm{F} \times \mathrm{r} \times (\sin\theta + \frac{\sin 2\theta}{2 \times n})$$

where, F = Total force over piston

r = crank radius

θ = crank angle

$n = \frac{length\ of\ connecting\ rod}{crank\ radius}$

On applying the values, we get: T = 21.98 Nm

Work done by the pressurized air over piston = F × stroke length = 39.09 Nm

Power transferred to the crankshaft = 2060 Nm/sec.

Angular velocity of crankshaft, $\omega = \frac{power}{torque}$ = 98.09 rad/sec.

R.P.M. of crankshaft, $N = \frac{\omega \times 60}{2\pi}$ = 940 rpm

We have taken an offset of 1 inch (0.0254 m), a link from the crankshaft center line, transferring motion to the direction control valve through a bell crank lever to facilitate for opening and closing of input port at the determined time.

For the calculated rpm, half of revolution would be completed in 0.03 sec. and thus the 2 inch (0.0508 m) movement of the pistons in direction control valve due to offset would get completed in 0.03 sec only.

Thus the pistons in direction control valve reciprocates at a speed of: 66.67 inch/sec : (1.69 m/sec)

Also, for the given angular velocity of crankshaft, the piston inside the engine cylinder slides with a speed = 2.67 m/sec.

Thus, time required for the piston to complete one stroke = $\frac{stroke\ length}{speed\ of\ the\ piston}$

= 0.019 sec.

From this, we conclude that piston require 0.019 sec of time to complete a stroke. Also, as we have single port for the inlet and outlet for the air, time required in which the inlet port should close for the exhaust to take place (when the piston would have travelled all the way to the BDC)would be equal to time required for a stroke to occur.

This gives us the distance between the one side piston of direction control valve and port which should be maintained for the required 2 stroke operation of the engine.

Thus the required distance between direction control valve piston and port = 1.26 inch

= 3.2004 cm

In this way, by limiting the distance between the direction control valve pistons and their distance from the piston bore center, we can ensure that the inlet/outlet port will be open to compressed air when piston is at TDC and will be open to exhaust pipe when piston is at BDC which will provide us with 2 stroke functioning of engine.

Final arrangement of direction control valve to assist 2 stroke operation of engine:

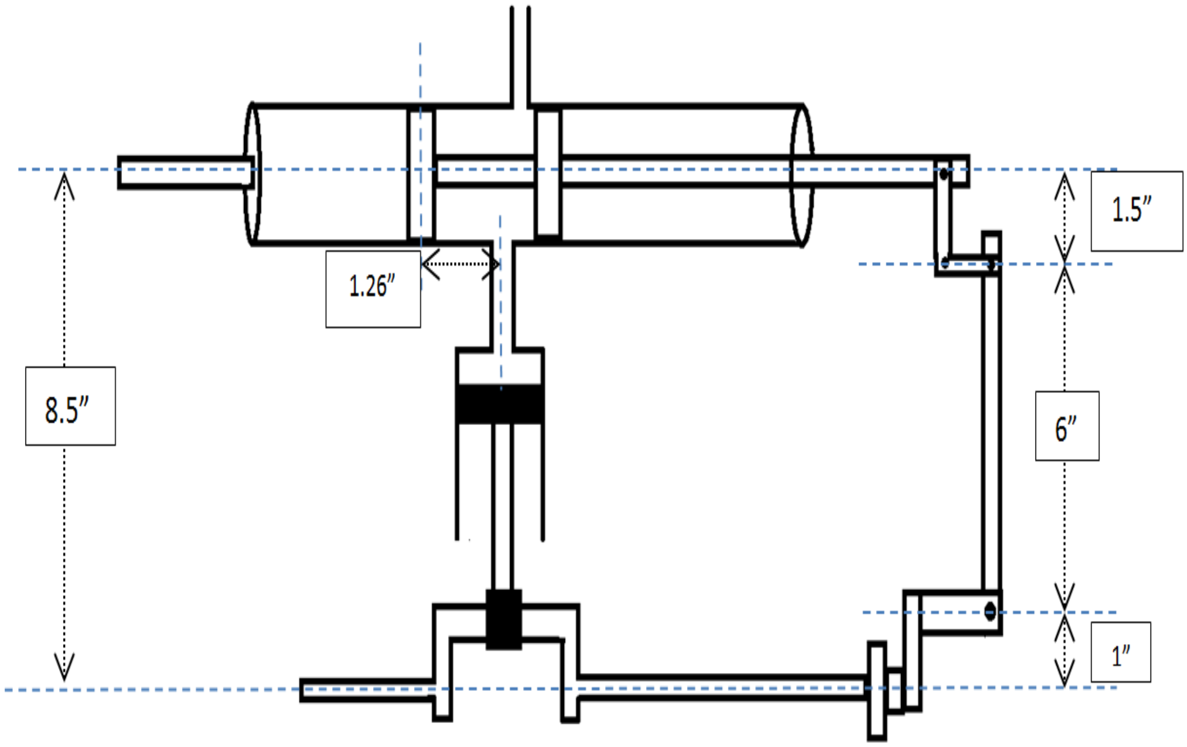


Figure 5.2 Final Dimensions of the CAE

CHAPTER 6

RESULTS AND DISCUSSIONS

6.1 GRAPHS AND THEIR SIGNIFICANCE

In this section we will discuss about various graphs which are either discrete (plotting using experiment) or continuous (plotted using co-relations) ,about their shapes, inferences drawn from the graphs. Maxima and minima if any and last but not the least the best suitable operating conditions. The graphs which are discrete are the ones which are experimentally plotted by changing a given variable. It is also tried to represent the variation between 3 variables on a 2-d curve. For experimental purpose the instruments mainly used are tachometer and dynamometer. There are 17 graphs plotted which includes firstly the variation of pressure with the charging and discharging time. After that comes the variation of rpm with the pressure and then comes the variation of torque, power and efficiency with the rpm. After that we try to change the % valve opening and studied same parameters i.e, power and efficiency and finally we plotted the analytical co-relations of various parameters.

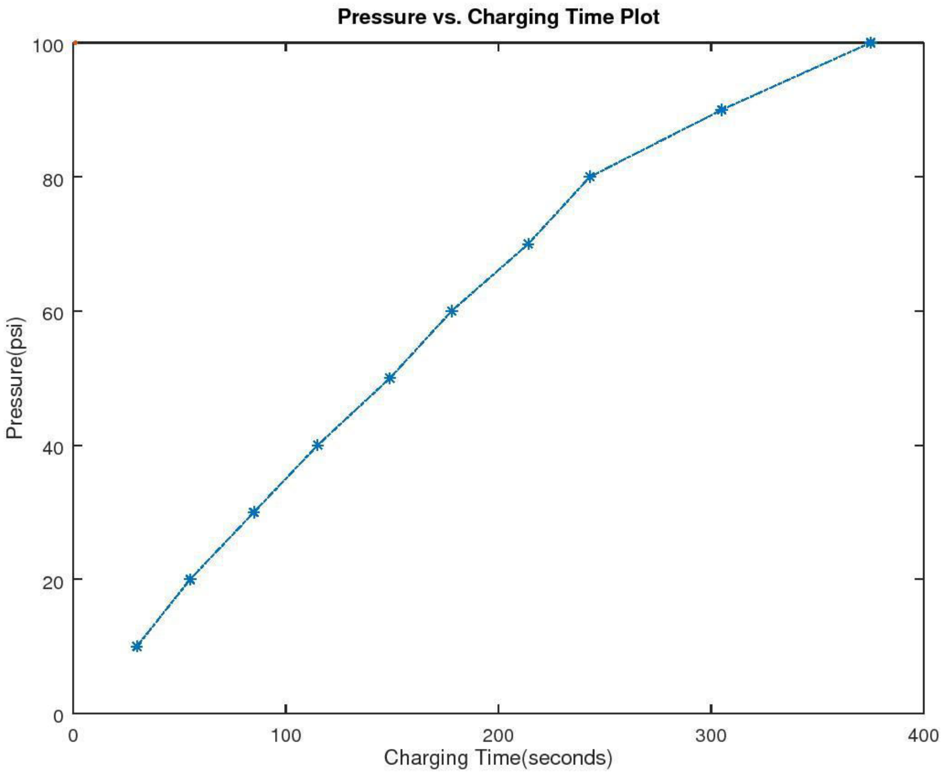


Fig. 6.1 Pressure vs. Charging Time Variation

The given plot is between the variation of pressure inside the compressor and the charging time. Charging time is the time required to attain a certain pressure in the compressor. The given plot is based on the experimental readings . As can be seen in the graph the total charging time is close to 370 seconds i.e., approximately 6 minutes. That is the compressor, of 25 litre of capacity, got fully charged in approximately 6 minutes. Also we can see from the graph the time required to rise certain pressure in the tank is less at the beginning and increases at the last because of the fact that initially the difference between inside and outside pressure is more, so the air flow rate is more and hence takes less time when compared with the last stage where the difference becomes very less and hence the flow rate becomes very slow.

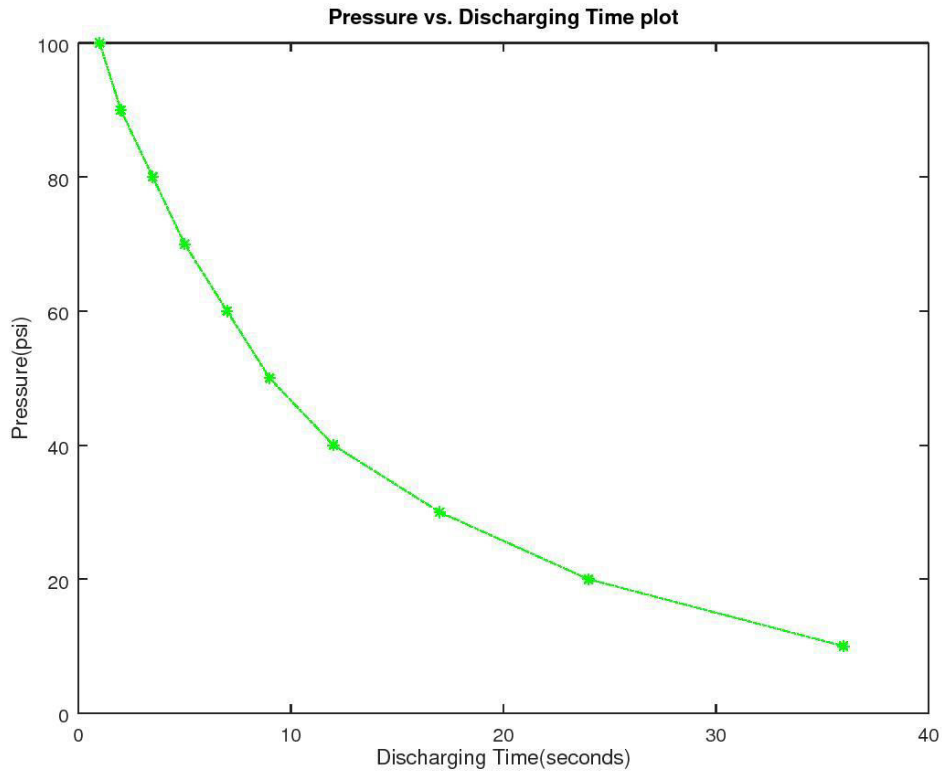


Fig. 6.2 Pressure versus Discharging Time Variation

The given plot is between the variation of pressure inside the compressor and the discharging time. Discharging time is the time required to discharge a certain pressure in the compressor. The given plot is based on the experimental readings . As can be seen in the graph the total discharging time is close to 34 seconds i.e., approximately half a minutes. That is the compressor, of 25 litre of capacity, got fully charged in approximately half a minutes.

Also we can see from the graph the time required to discharge up to certain pressure in the tank is less at the beginning and increases at the last because of the fact that initially the difference between inside and outside pressure is more, so the air flow rate is more and hence takes less time when compared with the last stage where the difference becomes very less and hence the flow rate becomes very slow.

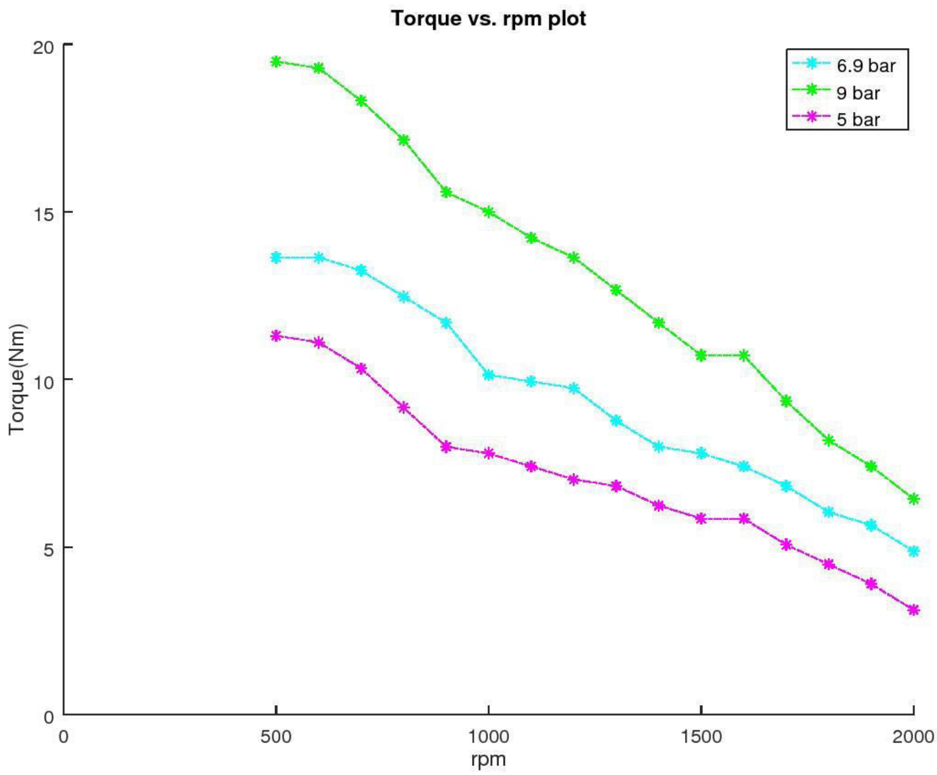


Fig. 6.3 Torque versus rpm Variation

The above given plot is between two important parameters i.e., Torque and crank shaft rpm. The given plot is a discrete plot and is obtained experimentally using the dynamometer. When we change the load, the torque changes and hence the rpm of the crankshaft which is measured using the tachometer. From the graph it can be seen that the maximum torque is approximately 20 N-m and occurs at 500 rpm and shows a decreasing trend after that. The decrease of torque with rpm can be attributed to the fact that the power available is constant. So if one variable increases other must decrease but the decrease is not hyperbolic because of the heat liberated due to friction.

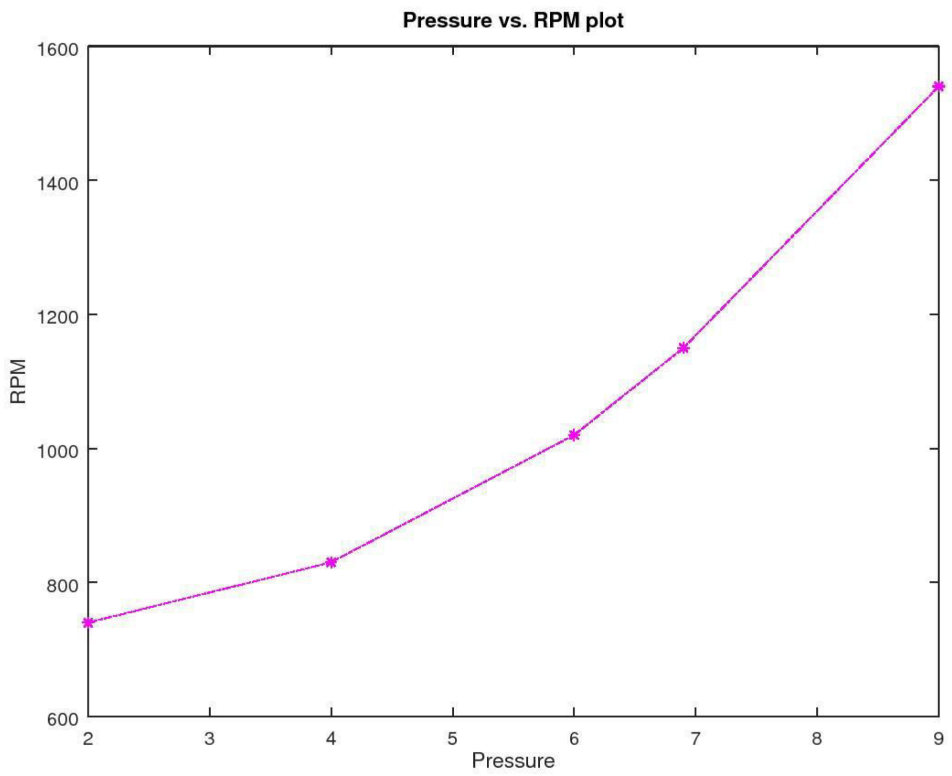


Fig. 6.4 RPM versus Pressure Variation

The above plot is between two important variables rpm and pressure. RPM of the engine is a direct function of pressure in the compressor. So we plotted a curve between the two. We operated our compressor at different capacities and correspondingly calculated the rpm using tachometer. In the graph we see an increase of slope, showing that the change in rpm is more at a higher pressure. Hence if we have to find the co-relation between the two variables, it will be parabolic in nature with its vertex at some offset to the origin. i.e,

$$\text{Rpm} = k\,(\text{Prr.})^n + c$$

Where,

k, n & c are positive constants

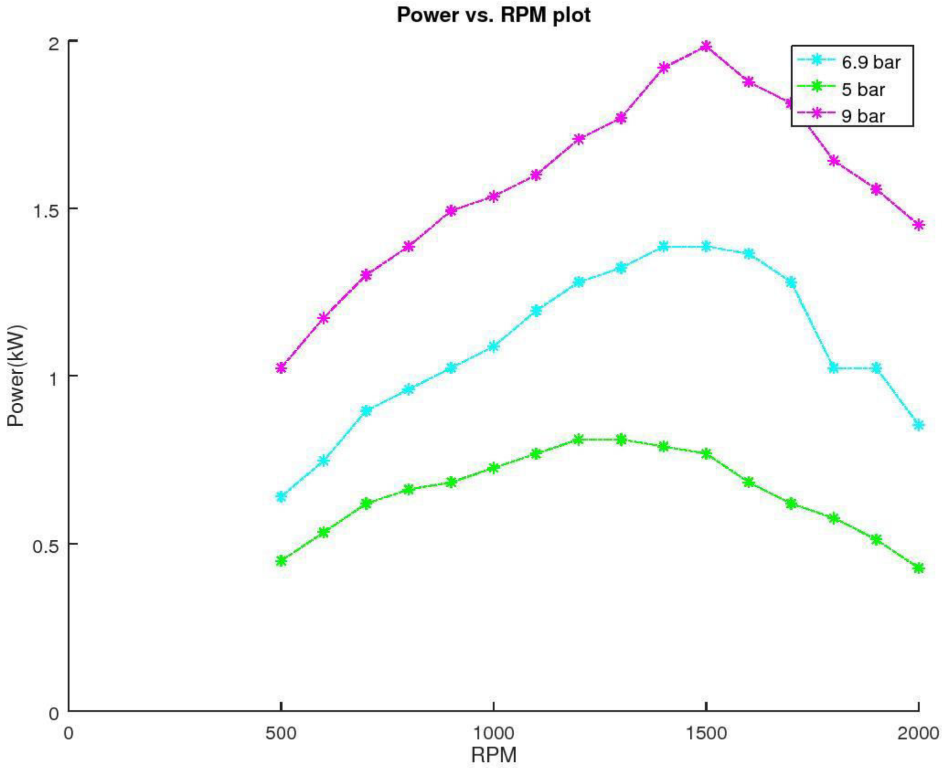


Fig. 6.5 Power versus RPM Variation

The above plot shows the variation of power with crank rpm. The above plot is analytic in nature and is plotted experimentally using the setup. As seen in the curve, power is minimum at the starting and end and rises to a maxima in between. So the importance of this curve is that we will find the rpm corresponding to which the power is maximum and will operate the engine at the same rpm so that we get maximum power output by minimizing the losses. Among the readings taken, we can see that the power is maximum at approximately 1000 rpm when operated at 100 psi. Also the maxima shifts towards left side when the pressure is decreased.

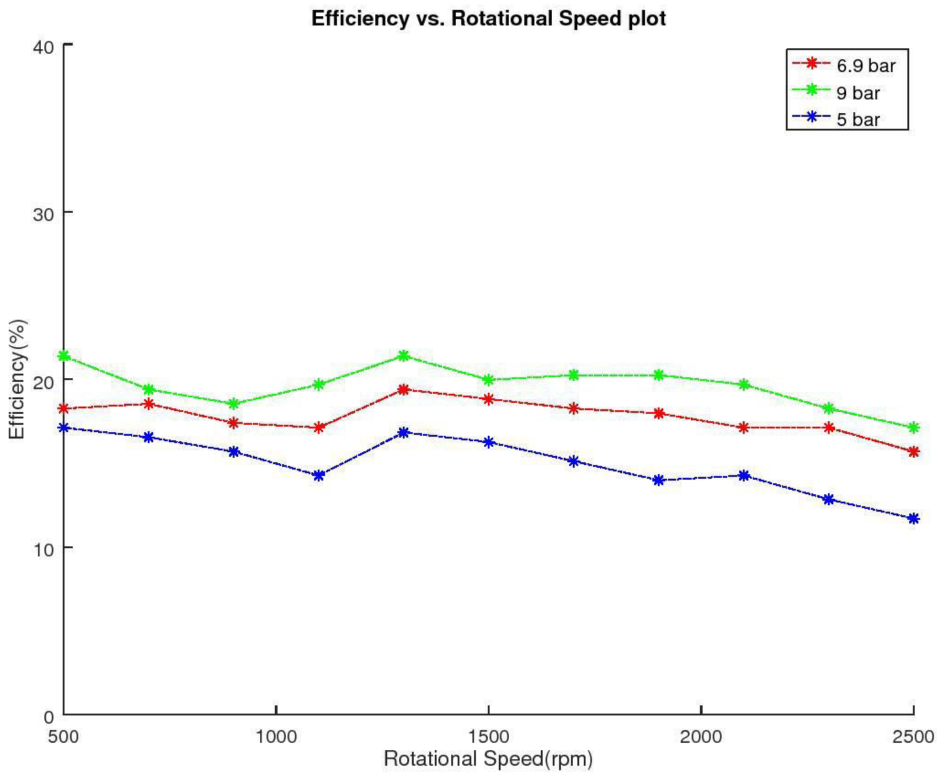


Fig. 6.6 Efficiency versus RPM Variation

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The above plot is between the efficiency of engine and rpm of the crankshaft. The given plot is a discrete one and is found experimentally for different values of rpm and pressure. It can be seen as the value of the pressure increases, for a given rpm, efficiency increases because of the increase of the force over the piston. The curve is plotted using the dynamometer at different loads. When we change the load, rpm of the crankshaft changes, and hence the efficiency of the engine .

Also it is seen that the efficiency starts decreasing above 2500 rpm. When compared between the three pressures max. efficiency occurs at 9 bar, having a value of approx 22%.

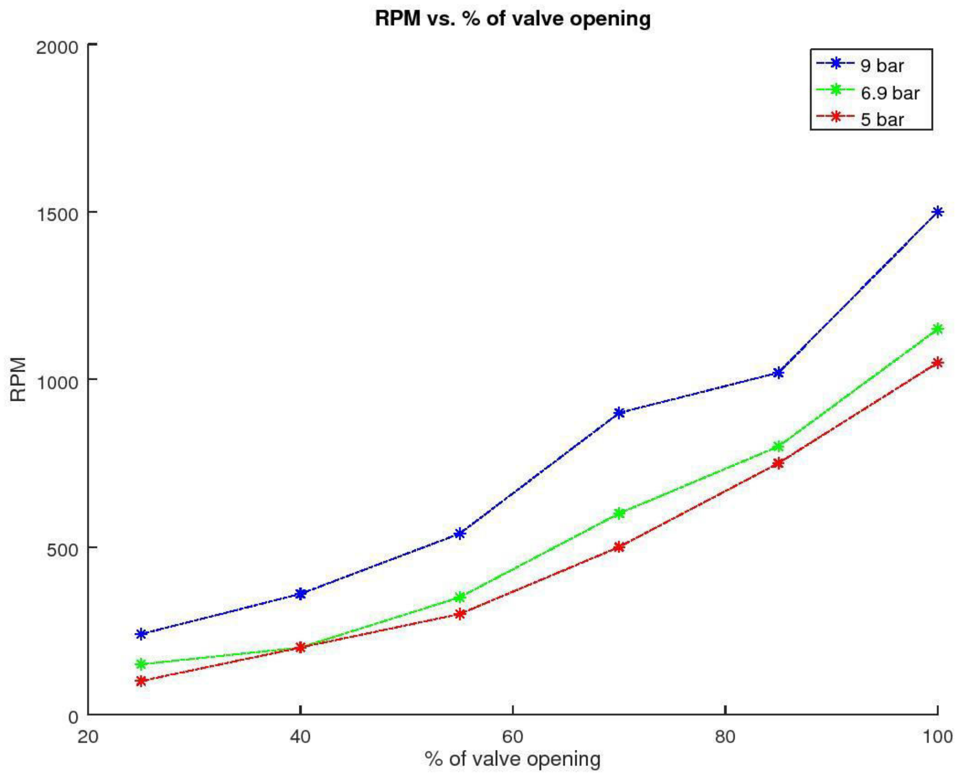

Fig. 6.7 RPM Versus % Valve Opening

The above plot shows the variation between the rpm and the % valve opening. The plot has been made by changing the position of the knob in order to control the discharge from the compressor. We can see an increase in the rpm with an increase of the valve opening because of the increase of discharge more pressure will be exerted over the piston and hence more rpm. When we increase the valve opening, rpm increases but the time for which engine works will decrease because of more discharge rate , cylinder will be emptied at a faster rate. It is also clear from the graph that the rate of increase of rpm with the increase of percentage valve opening i.e, at higher opening rpm will increase more rapidly. Among the readings taken maximum rpm occurs for a pressure of 9 bar (when the valve is 100% open) and minimum for 5 bar. So we will operate when the valve is 100 % opened in order to get maximum rpm

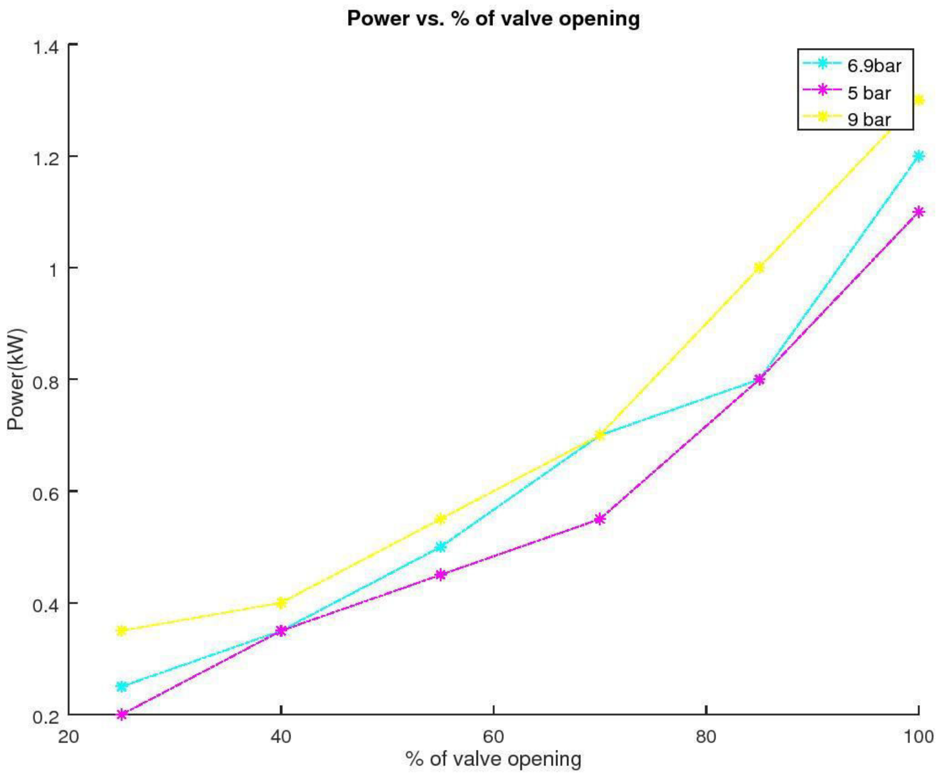

Fig. 6.8 Power versus % Valve Opening

The above plot shows the variation between the power and the percentage valve opening. The plot has been made by changing the position of the knob in order to control the discharge from the compressor. We can see an increase in the power with an increase of the valve opening because of the increase of discharge more pressure will be exerted over the piston and hence more power. When we increase the valve opening, power increases but the time for which engine works will decrease because of more discharge rate, cylinder will be emptied at a faster rate. It is also clear from the graph that the rate of increase of power with the increase of percentage valve opening i.e, at higher opening power will increase more rapidly. Among the readings taken maximum power occurs for a pressure of 9 bar (when the valve is 100% open) and minimum for 5 bar. So we will operate when the valve is 100 % opened in order to get maximum rpm

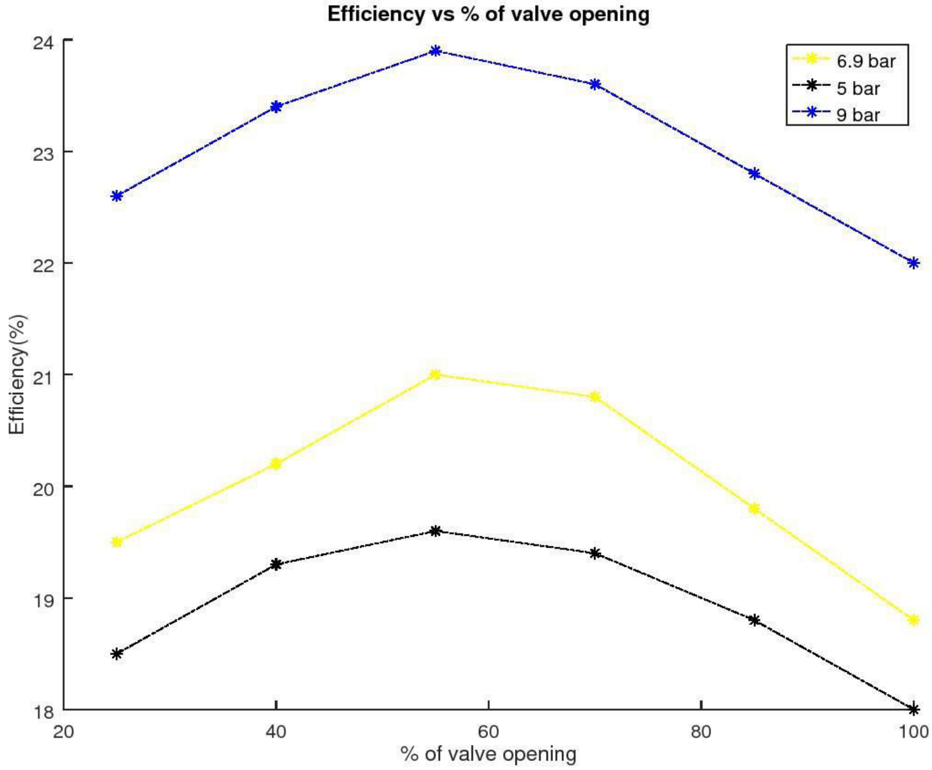

Fig. 6.9 Efficiency versus % Valve Opening

The above plot shows the variation of efficiency with % valve opening. The above plot is analytic in nature and is plotted experimentally using the setup. As seen in the curve, efficiency is minimum at the starting and end and rises to a maxima in between. The efficiency decreases on both sides because of time factor. So the importance of this curve is that we will find the % valve opening corresponding to which the efficiency is maximum and will operate the engine at the same opening so that we get maximum power output by minimizing the losses. Among the readings taken, we can see that the power is maximum at approximately 55 % valve opening when operated at 100 psi. Also the maxima shifts towards left side when the pressure is decreased.

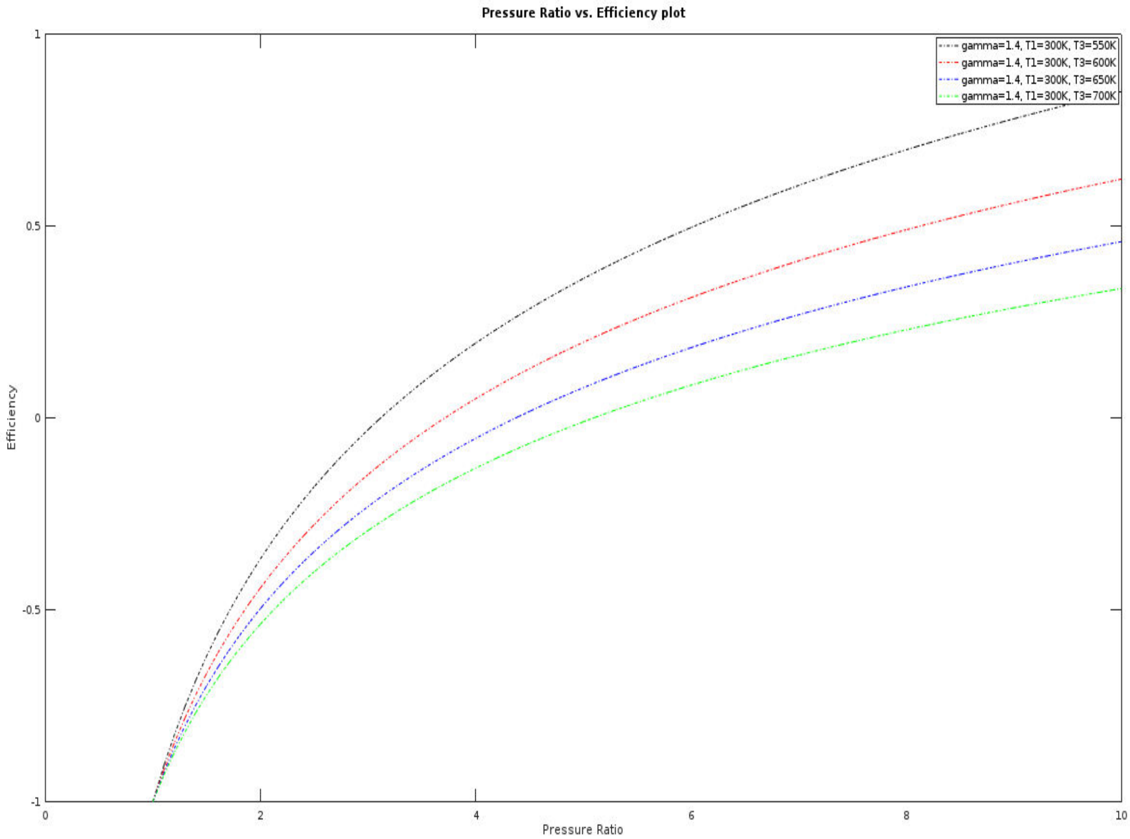

Fig. 6.10 Efficiency versus Pressure Ratio

The given figure shows the relationship between the efficiency and the pressure ratio. As can be seen in the graph efficiency increases with the increase in the pressure ratio but the rate of increase decrease with the pressure ratio. Also the efficiency is negative up to a pressure ratio of somewhere around 2 – 3 bar. This is because of the fact that if we run the engine at very low pressure than maybe the pressure energy is not able to overcome the friction forces but we are continuously supplying the energy. Hence the device becomes a energy consuming device without any significant output. Hence the efficiency comes out to be negative.

The desired co-relation connecting the two variables is –

$$\eta=1- T_{min.} [\ln(r_p)] / [(\gamma/\gamma-1)(T_{max}- T_{min}]- [T_{max}/ r_p^{(\gamma-1/\gamma)} – T_{min}]/(T_{max} – T_{min})$$

Graph shows how the efficiency increases with the decrease of maximum temperature in the engine.

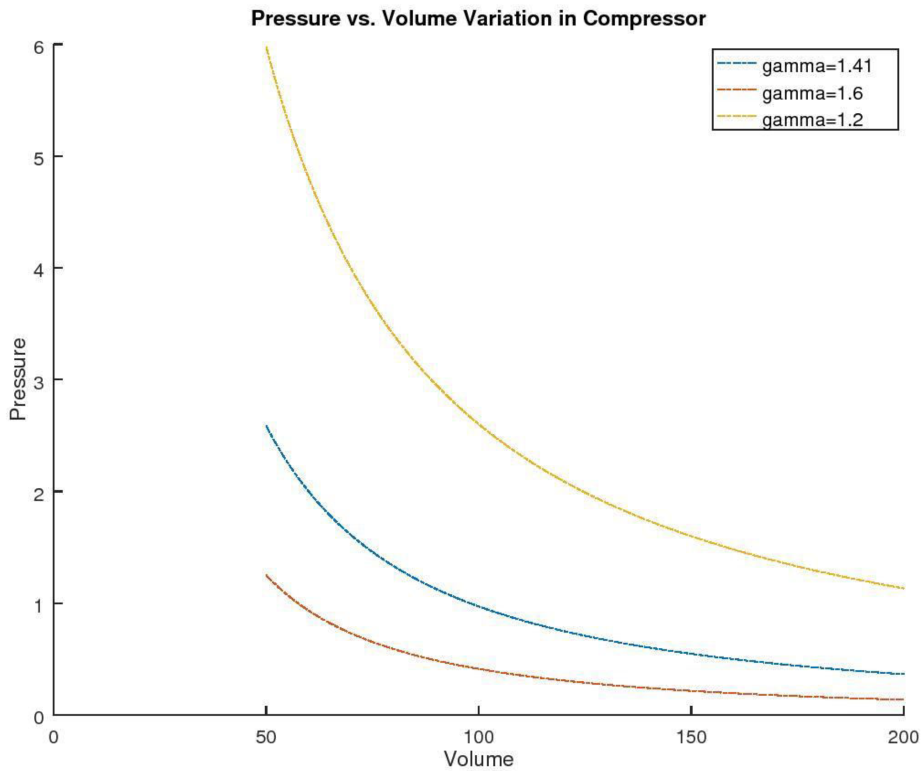

Fig. 6.11 Pressure versus Volume Variation

The plot above shows the relationship between the pressure inside the compressor for a given volume of gas. As we can see when the volume inside the compressor decreases the pressure increases according to the law $PV^{\gamma} = C$ .Also as we can see from the graph the increase in the pressure is less at the starting while the increases rapidly at the end due to the fact that the gas becomes incompressible at the end of the cycle leading to an higher increase of pressure. The curve also shows the relationship between pressure and volume for different types of gases viz., mono-atomic, di-atomic and tri-atomic. For the same amount of compression tri-atomic gas shows the maximum pressure rise, then comes and finally mono-atomic which shows minimum pressure rise. This is because of the fact that tri-atomic gas has three bonds and hence they acquire more space and are difficult to compress.

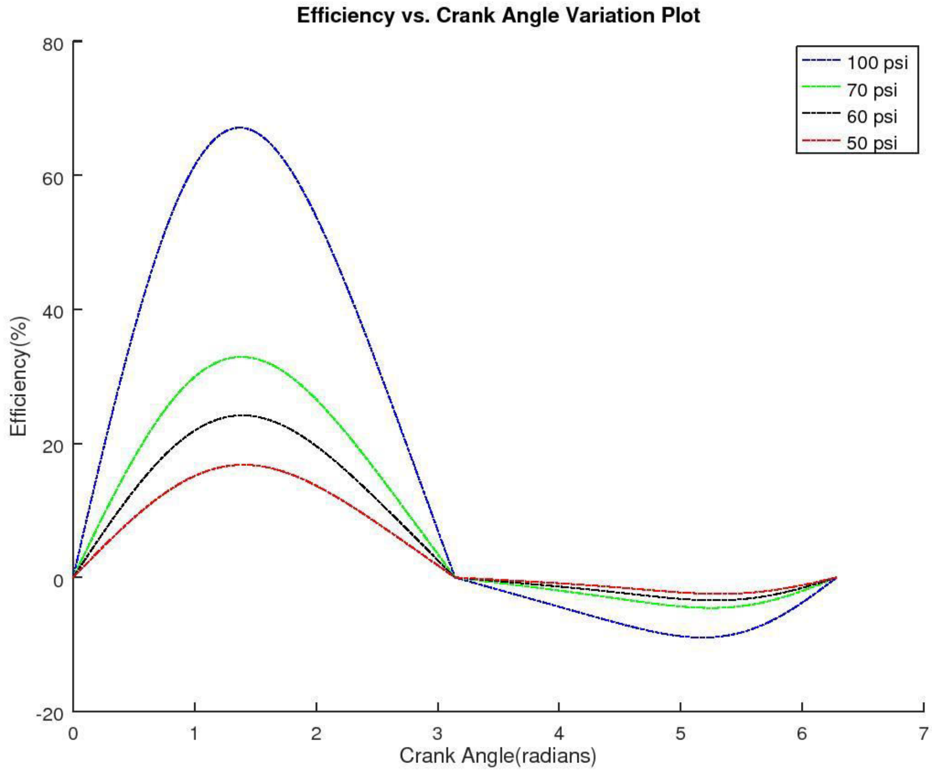

Fig. 6.12 Efficiency versus Crank Angle Variation

The above graph depicts the variation of efficiency with the crank angle at different pressures, The equation which depicts the relation between the two variables is -

$$\eta = \frac{P_{O/P}}{P_{I/P}} = \frac{\frac{\{ P_{stag.} A\,\omega - mr\omega^3 \left[\cos\theta + \frac{\cos 2\theta}{n}\right] - F_i \}}{\cos\left[\sin^{-1}\left(\frac{\sin\theta}{n}\right)\right]} \sin\left[\theta + \sin^{-1}\left(\frac{\sin\theta}{n}\right)\right]}{V * I}$$

As can be seen from the graph , efficiency is positive up to π radian and it becomes negative from π to 2π because of the fact that engine produces power from 0 to π radians because of the pressure energy of the compressor and from π to 2 π radians engine expels the expanded air in the chamber hence in this cycle it requires the energy stored in the flywheel, thus becoming an energy consuming device. Also as the pressure increases, efficiency increases because of the higher pressure more force and hence more power is produced. But the interesting thing which can be seen from the graph is the decrease in efficiency is also more at the higher pressure. This can be visualized using the fact that the energy required to expel the air at higher pressure is also more.

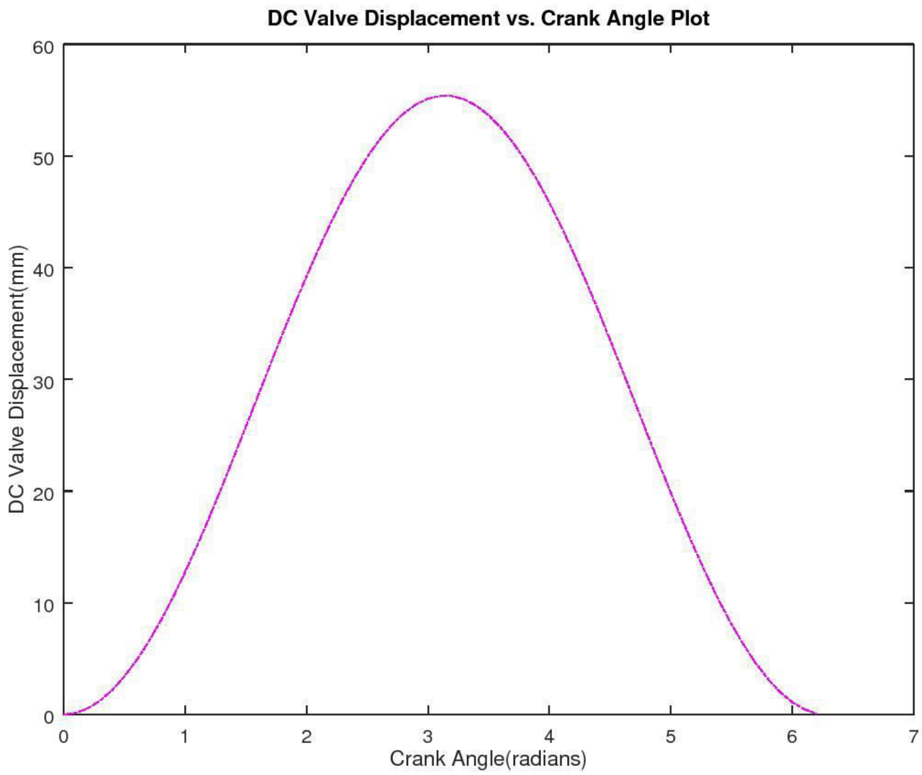

Fig. 6.13 DC Valve Displacement versus Crank Angle

The above graph is the plot between the displacement of directional control valve from extreme left position with the crank angle. As the crank starts rotating, directional control valve also starts moving because of the mechanism by which they are connected. The equation establishing the relation between the two variables is given by-

$$x = r(1 - \cos\theta)$$

As the crank rotates from 0 to π radian direction control valve reaches to the extreme right and cutoff the supply from the compressor so that the engine could expel the air from the engine. And now when the crank completes its remaining stroke directional control valve again reaches to its original position and in this way cycle continues. Total distance which the directional control move is approximately 55mm i.e, almost equal to crank dia.

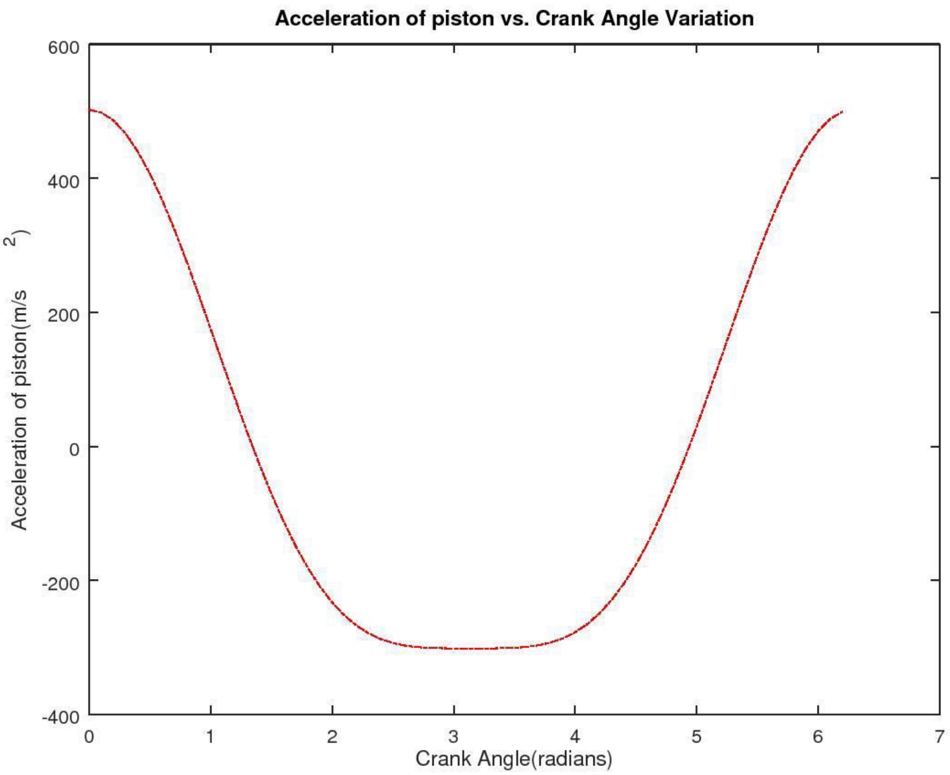

Fig. 6.14 Acceleration of Piston versus Crank Angle

The above plot depicts the relationship between acceleration of the piston and the crank angle. It can be visualized easily that with the change of the crank angle, acceleration of the piston changes. Since at the Top Dead Center (TDC) and the Bottom Dead Center (BDC) piston has to change its direction so the acceleration becomes zero at the extreme ends and maximum at the mid. Maximum acceleration as seen I the graph attained by the piston is around 500 m/s^2 .

The co-relation used for plotting the graph between the two variables is –

$$a = r\,\omega^2 \left[\cos\theta + \frac{\cos 2\theta}{n} \right]$$

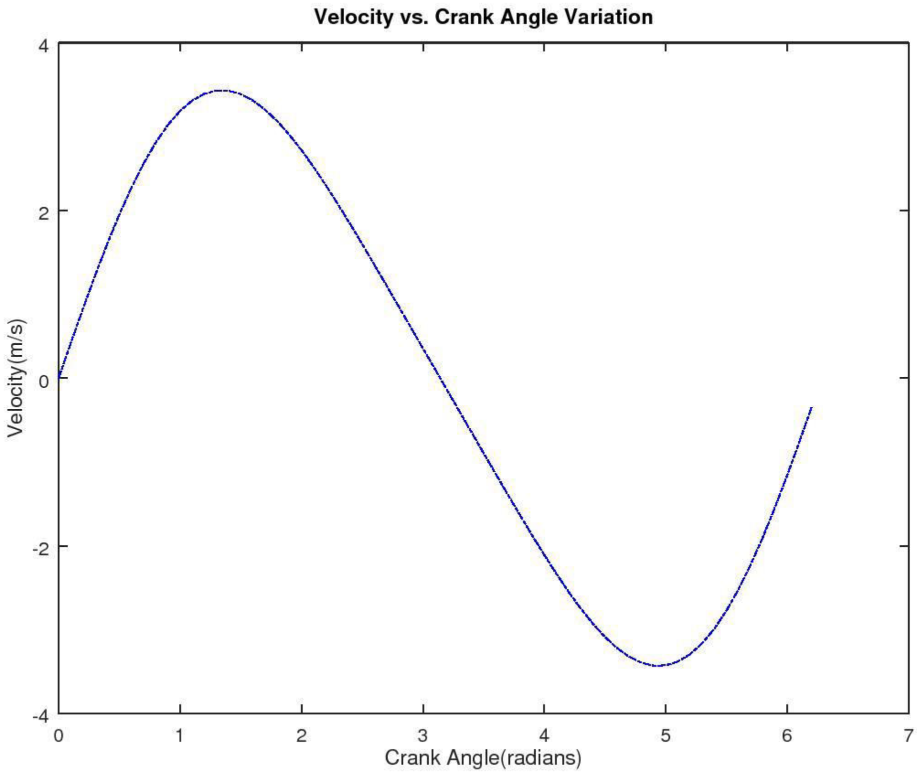

Fig. 6.15 Velocity versus Crank Angle Variation

Variation of velocity with the crank angle follows sinusoidal curve. The curve is basically one order higher derivative of the displacement – crank angle curve. The deriving equation for the curve is –

$$v = r\,\omega\,[\,\sin\theta + \frac{\sin 2\theta}{2n}\,]$$

When the piston is at TDC velocity of the piton is zero, now when the crank starts rotating velocity starts increasing and reaches to the maxima when the crank has turned a quarter. After that velocity starts decreasing because piston has to change its direction at the BDC, so the velocity finally becomes zero and then again increases magnitude wise and finally becomes zero. In this way the cycle continues like this. From the graph it can be seen that the maximum value of velocity attained by the piston is 3.34 m/s at $\frac{\pi}{2}$ and $\frac{3\pi}{2}$.

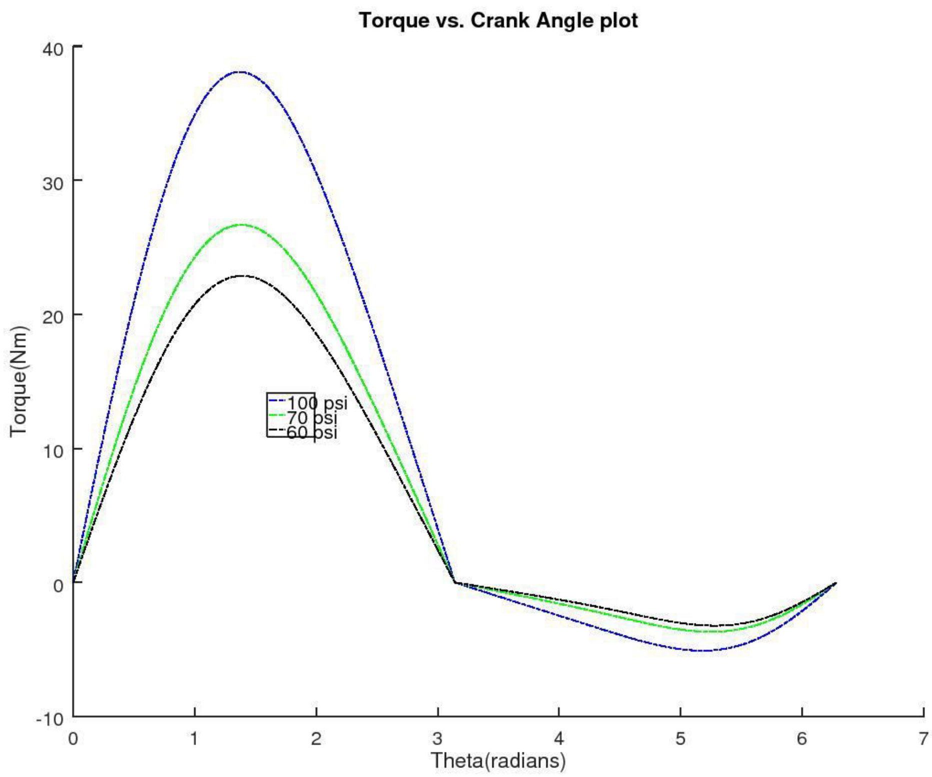

Fig. 6.16 Torque versus Crank Angle Variation

The given curve is between the torque and the crank angle. This curve shows how the torque varies with the crank rotation. As can be seen from the graph torque is positive in first half cycle and negative in second half cycle. This is because of the fact that in the first half cycle engine produces by using pressure energy from the compressor while in later half cycle, energy is required to expel the air inside the cylinder , due to which the torque is negative. The governing equation to establish the relation between the two variables is –

$$T = \frac{\left\{ P_{stag.} A - mr\omega^2 \left[\cos\theta + \frac{\cos 2\theta}{n} \right] - F_f \right\}}{\cos\left[sin^{-1}\left(\frac{sin\,\theta}{n}\right) \right]} \sin[\theta + \sin^{-1}(\frac{sin\,\theta}{n})]\ r$$

From the graph it can be seen that the maximum value of the torque is close to 40 N-m at approximately 100 psi. Maxima occurs at $\frac{\pi}{2}$ because at $\theta = \frac{\pi}{2}$, force acts perpendicular to the radius vector . Hence giving the maximum torque

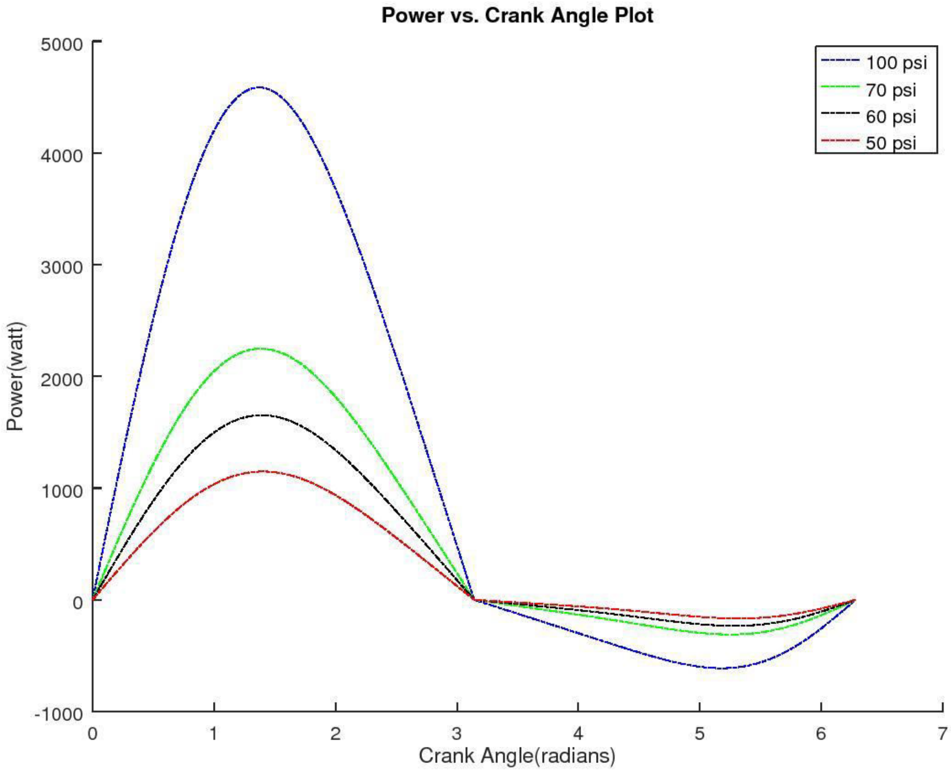

Fig. 6.17 Power versus Crank Angle Variation

The given curve is between the power and the crank angle. This curve shows how the power varies with the crank rotation. As can be seen from the graph power is positive in first half cycle and negative in second half cycle. This is because of the fact that in the first half cycle engine produces power by using pressure energy from the compressor while in later half cycle, energy is required to expel the air inside the cylinder , due to which the power is negative. The governing equation to establish the relation between the two variables is same as that of the torque & theta plot with a multiplication of angular velocity–

$$P = \frac{\left\{ P_{stag.} A - mr\omega^2 \left[\cos\theta + \frac{\cos 2\theta}{n} \right] - F_f \right\}}{\cos\left[sin^{-1}\left(\frac{sin\,\theta}{n}\right) \right]} \sin[\theta + \sin^{-1}(\frac{sin\,\theta}{n})]\ \omega r$$

From the graph it can be seen that the maximum value of the torque is close to 4700 W at 100 psi. Maxima occurs at $\frac{\pi}{2}$ because at $\theta = \frac{\pi}{2}$, force acts perpendicular to the radius vector . Hence giving the maximum power

6.2 PROBLEMS ENCOUNTERED

The technology of the air car has not been something which has been in use for a large period of time. There are many problems which are being encountered in the implementation of the technology. Some of them are briefed as follows –

- Air cars are yet not available in the most places but technology behind their working is being nurtured so that it is easy to introduce them in the market.
- Engines of the air cars is fueled by tanks containing compressed air, instead of an engine that runs with the fuel air mixture and piston.
- Vehicles running on compressed air sounds like amazing idea on paper, but practically bringing this technology for the masses has been proving, well, to be a difficult road because of some of the inherited technical complexities with the compressed air.
- The cars are basically designed for getting filled up at high pressure and thus there is a need of ensuring the appropriate safety standards for the designing purpose.
- The air storing tank can be made up of metal or that of composite. The fiber materials can be used instead because it is considerably lighter but has a drawback of being more expensive.
- Metal tanks have a high pressure withstanding capability, but are prone to corrosion and hence must be checked periodically for corrosion.
- Producing compressed air at very large pressures is very expensive and also gets inefficient for the use.
- The energy left for the working of engine is 20% of the input energy. That simply means that 80% of what is spent is used up and what we get at the output is 20%.
- If we want to use the air storage system in vehicles or in aircraft (for the practical land or for air transportation), for that energy storage system should be compact and also lightweight. Power required can also be controlled by using multistage compression of the air.

- The compression process generates heat, so there is a need to cool the compressed air between the stages in order to make the compression to be more isothermal.
- The inter-stage cooing typically leads to some partial condensation which is to be removed in the vapor-liquid separators.
- By inter stage cooling of the compressed air between various stages, the compression curve shifts to near isothermal. Thus making the work done by the compressor less for a multi-stage compression.
- When air expands inside the engine, air cools very fast and requires heating to reach the ambient temperature.
- There will be a necessity of complete dehydration inside the compressed air by using the heat exchanger.
- Refueling of the air container may take 3 to 4 hour if a home or some low end air compressor are used, even though some specialized equipment may fill tanks in less than 3 minutes at service stations

6.3 BENEFITS OF USING COMPRESSED AIR ENGINE

Broadly we are classifying the benefits of Compressed Air Engine into two categories i.e, Technical benefits and Economical Benefits.

6.3.1 Technical benefits:

- The working temperature of engine will be some what less than that of the ambient temperature.
- Engine works smoothly due to negligible wear and tear in the components.
- There are no chances of knocking.
- There is no need of cooling jackets, spark plugs, cylinder head, complex fuel injection systems and many other parts

6.3.2 Economic benefits:

- Expensive fossil fuels are not used as the air is being compressed and used which is free of cost.

- Because of this people can shift easily to this new technology.
- Compressors uses electricity for producing compressed air which is comparatively much cheaper and easily available.
- Smooth working of engine will lead to minimal amount of wear & tear, and hence lesser cost of maintenance.
- Cheaper in cost and also it doesn't cause harm to the environment.
- Thus it will make an important place for itself in the futuristic modes of transportation.
- Like electrical vehicles, in air powered vehicles also ultimate power will be through the use of electrical grid. So it is easier to focus on pollution reduction from one source, when compared to the millions of vehicles running on the roads.
- Fuel transportation will not be required because of drawing power from the electrical grid. This helps in significant amount of cost benefits. Also the pollution created due to the fuel transportation will also gets eliminated.
- Compressed air technology (CAT) also reduces the cost of vehicular production by approx 20%, since there is no requirement of building a cooling system, Ignition Systems or silencers, fuel tanks etc.
- Air, as we know, is non-flammable on its own.
- High torque achievable for minimum amount of volume.
- The design of engine is also simple and robust in nature.
- Low manufacturing and maintenance costs associated and also easy maintenance.
- Compressed-air tanks (made of metals or ceramics) are easily disposable and can be recycled with lesser amount of pollution compared to batteries.
- Compressed-air vehicles don't have degradation problems as are associated with the current battery systems.
- The tanks can be refilled very often and also in less time, when compared with the batteries which takes lot of time in recharging, having same re-fueling rates as that of liquid fuels.

- Lighter vehicles will also mean less amount of abuse on the roads, hence resulting in the longer lasting roads.
- The prices of fueling the air-powered vehicles as compared with the current fuels will have a significant difference.

6.4 LIMITATIONS OF USING COMPRESSED AIR ENGINE

There are many areas which needs to be worked on in order to successfully implement the technology. Some of the limitations of using compressed air engine are :

- When the air expands inside the engine, it cools rapidly and it's temperature should be brought to that of the ambient temperature.
- There is a necessity of complete dehydration inside the compressed air tank using the heat exchanger.
- Refueling of the air tank at home or with some low end air compressor may take long quiet somewhere up to 4 hours, but specialized equipment at the service stations can fill the tanks within 3 minutes.
- The overall efficiency of the compressed air vehicles by using the compressed air storage technique, using the earlier mentioned refueling figures comes out to be around 5-7%.
- For comparison purpose, if we talk about well to the wheel efficiency in case of conventional ic engines drive train it is about 14%,
- Early tests have shown that due to the limited air storing capacity of tanks, in some of the published tests for the vehicle running on the compressed air alone the range was limited to 7.22 km's

- Temperature Control—
    - In adiabatic processes of compressing the air, heat of the compression process is retained, that simply means, that there is basically no heat exchange and hence resulting in no entropy change if the process is reversible, so the temperature of the compressed air becomes high. Compressed air will experience the temperature rise because of the energy that is added to the gas from the compressor and it can be controlled using the isothermal or polytropic compression processes.

- In the isothermal compression processes, the gas used in the system is always maintained at constant temperature throughout the process. This requires that the heat must be removed from the gas. The process of heat removal can be attained using the heat exchangers (inter-cooling) in between the subsequent stages between the compressor. An adiabatic system of energy storage doesn't provide the inter-cooling when the compression process is taking place, and hence simply allows the temperature of the gas to be increased, and similarly cooling down during expansion. This is very attractive, because the loss of energy associated during the heat transfer can be avoided, but the downside of this is that the storing vessel must have insulation against the heat losses.

- Pollutant Emissions—

    - Like some of the other non-combustible energy storage techniques, an air vehicle shifts the source of emission from the tail pipe of vehicle to the central electricity generating plant where there is low emission sources available, net production of pollutants will beminimized. The emission control measures opted at the central electricity generating plant are more effective and costs than to treat the emissions of a largely dispersed vehicles.

    - Since the suction of compressed air is filtered in the compressor to protect it from dust and other particles, the air discharged from the engine has very less suspended particles in it, still there can be traces of lubricants used inside the engine.

6.5 APPLICATIONS

Compressed air technology finds its application in lot of sectors in present scenario, some are established and in some sectors it is still growing. Some sectors in which compressed air is predominately used is –

6.5.1 DRIVE FOR CONVEYORS

Air driven engines may be used in various types of conveyors for different drives like Belt conveyors, Screw conveyors, Chain conveyors etc., Generally it is used in slow speed applications. For medium load also it can be used.

Fig 6.18 Belt Conveyor [9]

6.5.2. JOB CLAMPING

In some operations such as in carpentry, job clamping requires low amount of loading. Air Driven Engines provide the low load clamping.

6.5.3. FLUID PUMPS

Air Driven Engine also finds its suitability in small displacement pumps of generally low pressure capacities.

6.5.4. AUTOMOBILES

The Air Driven Engine use is also possible for the two wheeler automobiles and for light motor vehicles.

Fig.6.19 Air Car [17]

CHAPTER 7

CONCLUSION AND FUTURE SCOPE

7.1 CONCLUSIONS

- This is a kind of revolutionary concept which is not only eco-friendly, but also very much economical.
- This redresses the biggest problems of now a days i.e, fuel crises and pollution. Yet some excessive research is required in order to completely establish the technology in terms of its commercial and technical viability.
- It can be seen that the indicated power is increasing for increase of load. As the load increases, speed falls down, in order to maintain it constant, the injection pressure must be increased.
- As the injection pressure is increased, the indicated mean effective pressure (i_{mep}) increases; and hence the indicated power increases upon application of the load.
- As load was applied the speed was reduced, to maintain it constant, the inlet air pressure has to be increased. As shown injection pressure is increased.
- As the output speed was less the brake power was significantly lower. The mechanical efficiency is increasing with the increase of output power. At lower output it was very low.

7.2 FUTURE SCOPES

- Design and fabrication of the engine made from light material will provide better results.
- Usage of the air tanks for the purpose of energy storage and supply would provide it more scope in the automobile sector.
- Much like the electrical vehicles, vehicles powered by air will also ultimately be powered using the electrical grid. So it is easier to focus on pollution reduction from one source, when compared with millions of vehicle running on the roads. Transportation of fuel will also not required because no fuel is used. This presents a significant amount of cost benefit. Also the pollution created during the transportation of fuel will also be eliminated.
- Air vehicles operate on simple thermodynamic process that air cools down during expansion and gets heat up when compressed. Since it's not possible in practical to use an ideal process because of losses and also improvement is involved in these processes, e.g., by using the heat exchangers to use the heat from ambient air and to provide the air cooling in passenger compartment simultaneously. On the other end, heat produced in the compression process can also be stored in the water systems, chemical or physical systems and can be reused later.
- New engine designs; as shown in the figure shows an improved variant of compressed air engines. With such type of engines; which are more efficient; air powered sector of automobiles can have a bright scope in near future.

Fig.7.1 Air Engine Variant

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APPENDIX

MATLAB PROGRAMME USED FOR PLOTTING GRAPHS

```
theta = 0:0.01:pi;

theta2 = pi:0.01:2*pi;


T1 = ((36.923-1.179*(cos(theta) + cos(2 .* theta) / 4)) ./ cos((asin(sin(theta) / 4)))) .*
sin(theta + asin(sin(theta) / 4));

K1 = ((-4.75 -1.179 * (cos(theta2) + cos(2 .* theta2)/4)) ./ (cos(asin(sin(theta2)/4))))
.* sin(theta2 + asin(sin(theta2) / 4));


plot(theta, T1*120.427, "-.b;100 psi;");

plot(theta2, -K1*120.427, "-.b");


T1 = ((25.846-1.179*(cos(theta) + cos(2 .* theta) / 4)) ./ cos((asin(sin(theta) / 4)))) .*
sin(theta + asin(sin(theta) / 4));

K1 = ((-3.325 -1.179 * (cos(theta2) + cos(2 .* theta2)/4)) ./ (cos(asin(sin(theta2)/4))))
.* sin(theta2 + asin(sin(theta2) / 4));


plot(theta, T1*84.29, "-.g;70 psi;");

plot(theta2, -K1*84.29, "-.g");
```

```
T1 = ((22.154-1.179*(cos(theta) + cos(2 .* theta) / 4)) ./ cos((asin(sin(theta) / 4)))) .*
sin(theta + asin(sin(theta) / 4));

K1 = ((-2.85 -1.179 * (cos(theta2) + cos(2 .* theta2)/4)) ./ (cos(asin(sin(theta2)/4))))
.* sin(theta2 + asin(sin(theta2) / 4));


plot(theta, T1*72.256, "-.k;60 psi;");

plot(theta2, -K1*72.256, "-.k");


T1 = ((18.46-1.179*(cos(theta) + cos(2 .* theta) / 4)) ./ cos((asin(sin(theta) / 4)))) .*
sin(theta + asin(sin(theta) / 4));

K1 = ((-2.375 -1.179 * (cos(theta2) + cos(2 .* theta2)/4)) ./ (cos(asin(sin(theta2)/4))))
.* sin(theta2 + asin(sin(theta2) / 4));


plot(theta, T1*60.213, "-.r;50 psi;");

plot(theta2, -K1*60.213, "-.r");


rpm = 500:100:2000;

t1 = 1.948 * [7, 7, 6.8, 6.4, 6, 5.2, 5.1, 5, 4.5, 4.1, 4, 3.8, 3.5, 3.1, 2.9, 2.5];

t2 = 1.948 * [10, 9.9, 9.4, 8.8, 8, 7.7, 7.3, 7, 6.5, 6, 5.5, 5.5, 4.8, 4.2, 3.8, 3.3];

t3 = 1.948 * [5.8, 5.7, 5.3, 4.7, 4.1, 4, 3.8, 3.6, 3.5, 3.2, 3, 3, 2.6, 2.3, 2, 1.6];


plot(rpm, t1, "-.*c;6.9 bar;");

plot(rpm, t2, "-.*g;9 bar;");
```

```
plot(rpm, t3, "-.*m;5 bar;");


p1 = 2.1327 * [0.3, 0.35, 0.42, 0.45, 0.48, 0.51, 0.56, 0.6, 0.62, 0.65, 0.65, 0.64, 0.6,
0.48, 0.48, 0.4];

p2 = 2.1327 * [0.21, 0.25, 0.29, 0.31, 0.32, 0.34, 0.36, 0.38, 0.38, 0.37, 0.36, 0.32,
0.29, 0.27, 0.24, 0.2];

p3 = 2.1327 * [0.48, 0.55, 0.61, 0.65, 0.7, 0.72, 0.75, 0.8, 0.83, 0.9, 0.93, 0.88, 0.85,
0.77, 0.73, 0.68];


plot(rpm, p1, "-.*c;6.9 bar;");

plot(rpm, p2, "-.*g;5 bar;");

plot(rpm, p3, "-.*m;9 bar;");


rpm = 500:200:2500;

e1 = 0.28525 * [64, 65, 61, 60, 68, 66, 64, 63, 60, 60, 55];

e2 = 0.28525 * [75, 68, 65, 69, 75, 70, 71, 71, 69, 64, 60];

e3 = 0.28525 * [60, 58, 55, 50, 59, 57, 53, 49, 50, 45, 41];


plot(rpm, e1, "-.*r;6.9 bar;");

plot(rpm, e2, "-.*g;9 bar;");

plot(rpm, e3, "-.*b;5 bar;");

axis([500, 2500, 0, 40]);
```

```
theta = 0:0.01:pi;

theta2 = pi:0.01:2*pi;


T1 = ((36.923-1.179*(cos(theta) + cos(2 .* theta) / 4)) ./ cos((asin(sin(theta) / 4)))) .*
sin(theta + asin(sin(theta) / 4));

K1 = ((-4.75 -1.179 * (cos(theta2) + cos(2 .* theta2)/4)) ./ (cos(asin(sin(theta2)/4))))
.* sin(theta2 + asin(sin(theta2) / 4));


plot(theta, T1*120.427*0.01463, "-.b;100 psi;");

plot(theta2, -K1*120.427*0.01463, "-.b");


T1 = ((25.846-1.179*(cos(theta) + cos(2 .* theta) / 4)) ./ cos((asin(sin(theta) / 4)))) .*
sin(theta + asin(sin(theta) / 4));

K1 = ((-3.325 -1.179 * (cos(theta2) + cos(2 .* theta2)/4)) ./ (cos(asin(sin(theta2)/4))))
.* sin(theta2 + asin(sin(theta2) / 4));


plot(theta, T1*84.29*0.01463, "-.g;70 psi;");

plot(theta2, -K1*84.29*0.01463, "-.g");


T1 = ((22.154-1.179*(cos(theta) + cos(2 .* theta) / 4)) ./ cos((asin(sin(theta) / 4)))) .*
sin(theta + asin(sin(theta) / 4));

K1 = ((-2.85 -1.179 * (cos(theta2) + cos(2 .* theta2)/4)) ./ (cos(asin(sin(theta2)/4))))
.* sin(theta2 + asin(sin(theta2) / 4));


plot(theta, T1*72.256*0.01463, "-.k;60 psi;");
```

```
plot(theta2, -K1*72.256*0.01463, "-.k");

T1 = ((18.46-1.179*(cos(theta) + cos(2 .* theta) / 4)) ./ cos((asin(sin(theta) / 4)))) .*
sin(theta + asin(sin(theta) / 4));

K1 = ((-2.375 -1.179 * (cos(theta2) + cos(2 .* theta2)/4)) ./ (cos(asin(sin(theta2)/4))))
.* sin(theta2 + asin(sin(theta2) / 4));

plot(theta, T1*60.213*0.01463, "-.r;50 psi;");

plot(theta2, -K1*60.213*0.01463, "-.r");

percent = [25, 40, 55, 70, 85, 100];

rpm1 = [150, 200, 350, 600, 800, 1150];

rpm2 = [200, 300, 450, 750, 850, 1250];

rpm3 = [100, 200, 300, 500, 750, 1050];

plot(percent, rpm2, "-.*b;9 bar;");

plot(percent, rpm1, "-.*g;6.9 bar;");

plot(percent, rpm3, "-.*r;5 bar;");

p1 = 1.083 * [0.25, 0.35, 0.50, 0.70, 0.80, 1.2];

p2 = 0.6363 * [0.20, 0.35, 0.45, 0.55, 0.80, 1.1];

p3 = [0.35, 0.4, 0.55, 0.7, 1.0, 1.3];

plot(percent, p1, "-.*c;6.9bar;");
```

```
plot(percent, p2, "-.*m;5 bar;");

plot(percent, p3, "-.*y;9 bar;");


e1 = 1.026 * [14, 15, 19, 17, 14, 12];

e2 = [13, 15, 18, 16, 12, 10];

e3 = 1.1 * [15, 18, 20, 18, 15, 13];


e1 = [19.5, 20.2, 21, 20.8, 19.8, 18.8];

e2 = [18.5, 19.3, 19.6, 19.4, 18.8, 18];

e3 = [22.6, 23.4, 23.9, 23.6, 22.8, 22];


plot(percent, e1, "-.*y;6.9 bar;");

plot(percent, e2, "-.*k;5 bar;");

plot(percent, e3, "-.*b;9 bar;");


rpm = [1540, 1150, 1020, 830, 740];

pres = [9, 6.9, 6, 4, 2];


plot(pres, rpm, "-.*m");
```